A Risk-Based Approach to Control of Water Quality Impacts Caused by Forest Road Systems

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June 2005

A thesis submitted for the degree of Doctor of Philosophy
The Australian National University

THE AUSTRALIAN NATIONAL UNIVERSITY

Frontispiece: An Example of the Stromlo Forest road, ACT, Australia, located near Mount Stromlo showing typical rill and gully occurrence on the surface of the road (March 2003).

Statement of Originality

I hereby declare that this work is my own original work and to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree or diploma of a university or other institution, except where specific acknowledgement is given.

Concepts, preliminary experiments with risk assessment and the need to apply them in this study, quoted in Chapters 2, 4 and 6 were used to prepare a paper presented at the Second Conference on Forest Engineering, 12 – 15 May 2003, Vaxjo, Sweden. Parts of Chapters 6 and 7 were used to prepare a paper presented in International Congress on Modelling and Simulation (MODSIM2003), 14 – 17 July 2003, Townsville, Australia. Parts of the results discussed in Chapters 5, 6 and 7 were used to write an abstract, which was accepted for a poster presentation at the Twenty Eighth Hydrology & Water Resources Symposium, 10 – 13 November 2003, Wollongong, Australia. Concepts and results from road and stream connectivity assessment presented and discussed in Chapters 4 and 7 were used to prepare and present a paper to the Fourth Australian Stream Management Conference, 19 – 22 October 2004, Launceston, Australia. The distance calculation and roads and stream modelling presented in Chapter 7 were used to write and present a paper at the International Conference on Simulation and Modelling (SimMod2005), 17 – 19 January 2005, Bangkok, Thailand. Overall concepts and results presented in this thesis were used to present a poster at the Twenty Second IUFRO World Congress, 8 – 13 August 2005, Brisbane, Australia. Parts of the final results of risk assessment presented in this thesis were used to write a paper which was presented at the International Congress on Modelling and Simulation (ModSim2005), 12 – 15 December 2005, Melbourne, Australia.

Signed: Houshang Parsakhoo (signature) ---------- Date: --------------

Acknowledgements

I would like to thank Dr. Ryde James, my principal supervisor (Senior Lecturer, School of Resources, Environment and Society (SRES), the ANU) and, after his retirement, the Head of SRES professor Peter Kanowski. Both academics have patiently given much help toward the completion of this thesis. Dr. Robert McCormack (CSIRO, Forestry and Forest Products (FFP)), a member of my supervisory panel, has kindly encouraged, helped and guided me, especially in the preparation of the technical framework of the thesis, the field survey, and structure of the thesis. The thesis would have been impossible without the continued help, support, patience and encouragement of all three supervisors. I appreciate their help greatly.

I express my deep appreciation and gratitude to Dr. Brian Turner (SRES, ANU), who has kindly reviewed the drafts of the thesis and offered many useful technical suggestions. I would like to thank Dr. Jacky Croke (The University of New South Wales (UNSW), Australian Defence Force Academy (ADFA)), who also made many technical suggestions, especially during the first steps of structuring and launching the thesis. I would like to express my deepest gratitude and appreciation to Dr. Cris Brack (SRES, ANU), and Dr. Jeff Wood (Statistical Consulting Unit, ANU), who have kindly and patiently provided statistical assistance. Dr. Ingrid Takken (UNSW, ADFA) has been a great source of scientific support. She also helped and encouraged me in the preparation of this thesis: I appreciate her help greatly.

Professor Peter Kanowski, in his role as the Head of SRES at ANU, provided much moral, technical and logistical support, especially the earlier part of my study, and in the final stages of thesis preparation. I greatly appreciate his help. I would like to express my deepest gratitude and appreciation to Dr. Sue Holzknecht from SRES, ANU, who has kindly and patiently reviewed, edited and proof-read the drafts of the thesis. The thesis would have not been completed without her continued help in English and editing and proof reading. I appreciate her help greatly.

I would also like to thank all the administration staff of SRES and my friends, at the office and home who have morally and technically supported, helped and offered many suggestions during the study. I thank them very much. In particular, I thank Dr. Richard Greene, SRES Graduate Advisor.

I would like to thank FFP, CSIRO for providing great scientific and logistic support for the study, especially while gathering data from the field, and for their friendly support and backing. My deep appreciation and gratitude go to: Mr. Andrew Winter (Senior Forester, ACT Forests) for his kind help and providing the information in relation to the study area (Stromlo Forest); all staff of ACT Forests for their support; NSW National Parks and Wildlife Service (NPWS) for the permission to use the images and datasets related to the area.

I gratefully thank Professor Javad Farhodi and Professor Ali Kohian, the previous and the present Academic Representative and Director of Iranian Students in Australia and Malaysia from the Ministry of Science, Research and Technology of Iran and other staff of the Ministry for their support and help to the scholars abroad. I also wish to express my gratitude to Gorgan University of Agricultural Sciences and Natural Resources, Iran, for the permission and for providing financial support to continue my studies as a PhD student. I appreciate all of the help and support from the university greatly.

I would like to express my special and cordial thanks to my wife, Fatemeh and my sons, Parsa and Parham for their continuous great support. The completion of thesis would have been impossible without their continued help, support, encouragement and patience; their time and holidays have been sacrificed for the progress and completion of the thesis. I also wish to express my deep appreciation and gratitude to all of my family back in my country Iran, especially our parents and our relatives here in Australia, for their continuous help and moral support.

Finally, I thank many other friends, who have not been named here, for their scientific and moral help and support. I thank them very much.

Dedication

This dissertation is dedicated to Fatemeh, my beloved wife, Parsa and Parham, my children, without whom this thesis could not have been completed. I dedicate this work to their encouragement, understanding and continual support.

Abstract

Most forestry production systems use extensive networks of unsealed roads for timber harvesting and other forest management activities. These road networks can be significant sources of runoff and sediment delivery to streams, causing deterioration of the quality of stream water. The extent of these impacts depends not only on the magnitude of road-derived runoff and erosion, but also on the degree of connectivity between the roads – the main source of sediment – and the streams. Several methods have been developed for identifying the extent of this connectivity.

The objective of this study is to demonstrate that information about sediment production from the road surface, about the delivery of runoff from the road drainage structures, and about road to stream pathways, can be analysed to predict the risk of sediment being deposited in streams. The hypothesis tested in this study is that, by analysing the attributes of an unsealed forest road and its surrounding terrain, it is possible to evaluate the risk that erosion from the surface of the road, or associated with the road drainage structures, will deposit water-borne sediment into an adjacent stream. This research reported in this study evaluates the use of statistical and GIS modelling approaches, within the context of a risk assessment framework, to identify the unsealed forest road segments that have the most impact on stream water quality.

The methodology applied in the study involves the following steps: determination of the experimental approach and design, and the sampling strategy; terrain modelling and analysis; forest road analysis; hydrological analysis; development of risk models for the occurrence of rill and gully erosion and road-to-stream connectivity; and risk assessment and mapping. The research was conducted at a case study site in Stromlo Forest, Australian Capital Territory, on the western edge of Canberra, Australia.

The experimental approach and strategy used in this study proved to be effective, and provided the data needed to analyse road and drainage structures, and test the hypothesis posed in the study. Data were collected from a random sample of 102 km of road segments;

the sample set comprised 685 road drainage structures that were partitioned into 'development' and 'validation' data sets. Geographical Information Systems (GIS) and Digital Terrain Modelling (DTM) were used to derive and calculate the terrain attributes from a Digital Elevation Model (DEM). The DTM approach, using relief analysis, demonstrated that using a combination of GIS techniques and mathematical modelling is the most accurate and fastest way to calculate the terrain parameters needed for the risk assessment of forest roads. The road analysis provided the basic information and data needed for selecting the road segments for sampling and analysis, and developing of a comprehensive road and drainage database. GIS-based models and hydrologic analysis were used to carry out watershed delineation, predict road-to-stream hydrologic distance, and assess road-to-stream connectivity. The road-to-stream connectivity assessment showed which sections of the roads are most likely to deliver sediment associated with runoff to a stream. Logistic models to predict the probability of rill and gully occurrence on the road surface and at the outlets of road drainage structures, and road-to-stream connectivity, were developed and validated from terrain parameters, outcomes of the hydrologic analysis, and field data. The models developed from the 'development' data set were found to correctly predict outcomes in the 'validation' data set on more than 96% of occasions.

The research also developed a specific risk assessment process for surveying, assessing and gathering data from road prisms. The potential for losing soil from the surface of the study area and forest roads was assessed using the Revised Universal Soil Loss Equation (RUSLE). This surface erosion assessment provided a preliminary soil loss risk map showing the areas sensitive to surface erosion, and the roads more likely to have rill or gully erosion. The variables influencing erosion or road-to-stream connectivity were used, in conjunction with risk assessment procedures, to create a risk map for each risk component. The risks represented by these separate maps were integrated to create a final consolidated risk map, which identifies the segments of the roads at most risk. This consolidated risk map integrates predictions of the probability of erosion occurrence, and of the degree and type of road-to-stream connectivity, to predict the probability and degree of erosion-induced sediment impacts on stream water quality. This risk map represents a simple and practical tool for identifying the segments of the roads where management for risk mitigation is critical.

The production of the consolidated risk map represents the final step in the research process. The overall processes can be represented and described in a single framework, called the Forest Road Impact Assessment (FRIA). The FRIA approach offers a useful systematic means for identifying, evaluating and managing the erosion risk associated with both existing and proposed roads. In doing so, the methodology has achieved the objectives of the study and demonstrated that the hypothesis underlying it is sound. One of the principal benefits of this method is that the time and cost of fieldwork required for unsealed forest road management can be reduced. Other significant advantages of the FRIA approach are that it is flexible in its applications, and that its outputs are easily understood by forest managers.

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List of Symbols, Acronyms and Abbreviations

ACT	Australian Capital Territory
ANU	Australian National University
APFC	Asia-Pacific Forestry Commission
BFM	Best Forest Management
cm	Centimetre
CSIRO	Commonwealth Scientific and Industrial Research Organization
CTI	Compound Topographic Index
DEM	Digital Elevation Model
DGPS	Deferential Global Positioning System
DTA	Digital Terrain Analysis
DTM	Digital Terrain Modelling
FAO	Food and Agriculture Organization of the United Nations
FRIA	Forest Road Impact Assessment
FFP	Forest and Forestry Products
GIS	Geographic Information System
GPS	Global Positioning System
ha	Hectare
ISO	International Organization for Standardization
ITTO	International Tropical Timber Organization
km	Kilometre
m	Metre
NSW	New South Wales
RCA	Road contributing area
RCL	Road contributing length
SCA	Specific Catchment Area
SFM	Sustainable Forest Management
SFMA	Stromlo Forest Management Area
SPI	Stream Power Index
SRES	School of Resources, Environment and Society
TA	Terrain Analysis
TWI	Topographic Wetness Index
USCA	Upslope Contributing Area

Chapter 1
Why Forest Roads and Water Quality Impacts?

1.1 Introduction – Why this Topic?

It is clear that many environmental problems, such as soil erosion and poor water quality, are related to human activities. For the last several decades, the public has become increasingly concerned about natural resource degradation. A critical question facing all forest managers and researchers is 'how can we find the best way to use natural resources in a more environmentally friendly way?'. Natural resource management activities can have both positive and adverse environmental impacts. This is the case in forest management, where it is necessary to understand both the negative and the positive results of forest activities like forest road construction and maintenance, logging, and forest transportation systems. Forest managers must also manage the relationship between their forest management objectives, the roles of technology, and the concerns of the public about the impact of forest activities.

Particular forest management activities pose particular environmental risks. Forest roads and timber harvesting activities can generate high risks to soil and water values. Consequently, water quality impacts caused by forest road systems have become a major topic for environmental research in the last two decades. This problem has recently been well defined and described by researchers such as Elliot and Hall (1997), Croke *et al.* (1999), Croke and Mockler (2001), Macdonald *et al.* (2001) and Takken *et al.* (2005). All agree that the principles of environmentally sustainable forest road management systems require the protection of soil and water values, as well as other environmental values.

The challenge to road planners and managers is to reduce impacts of roads on soil and water quality, given the constraints of road maintenance budgets and operational needs of road uses. The problems which forest road planners and managers face can be divided into three groups: providing continuous access along roads, reducing the expense of road maintenance, and reducing the impacts of roads on soil and water quality.

Despite many studies of the impacts caused by forest road systems on water quality, implementing good practices in the construction and maintenance of unsealed forest roads still remains expensive and difficult. In particular, as Croke and Mockler (2001) have argued, it is difficult to understand the behaviour of water flow pathways in forests, and how these pathways will be affected by management practices. This is a crucial issue for forest managers because it is these pathways that deliver sediment to streams, adversely impacting water quality.

Advances in spatial technologies and modelling, including spatial topographic modelling, Digital Terrain Modelling (DTM), and Geographic Information System (GIS), provide powerful tools to help forest researchers and managers address these issues. This study takes advantages of these new technologies to develop a method that incorporates predicted water flowpaths and which can be used by forest road managers as a practical tool for risk assessment.

This chapter introduces the rationale for developing a set of methods for assessing sections of a forest road and determining the variables influencing the impacts of forest road systems on the elements at risk, that is, soil and water. These methods include gathering data from the field and using geospatial techniques and tools.

1.2 Aim of this Study

The aim of this study is to assist forest managers to minimise the risk of forest roads impacting adversely on soil and water. When stated formally, the hypothesis on which this thesis is based is: that by analysing the attributes of an unsealed forest road and its surrounding terrain, it is possible to evaluate the risk that erosion from the surface of the road, or associated with the road drainage structures, will deposit water-borne sediment into an adjacent stream.

In this context, 'analysing terrain attributes' means using terrain modelling and spatial analysis techniques incorporated into GIS to describe and quantify features of different terrains. It also refers to adapting existing models or developing new ones to predict the circumstances in which risk thresholds will be exceeded.

In order to test this hypothesis, a case study was conducted using the roading system in Stromlo plantation forest, near Canberra in the Australian Capital Territory, Australia. Data describing the location of roads[1] [1]were available from GIS-based maps of the area. Additional data describing the roads and their drainage structures were collected from the field using a Differential Global Positioning System (DGPS) to locate features. Measurements of the effects of roads on soil and water were taken in the field. At the commencement of the data collection it was not known which terrain factors exerted the most important influence on deposition of sediment into streams, as there were no definitive indications from the literature. Data collection therefore had the objective of documenting any characteristic that could possibly have an influence on stream sedimentation and that could be measured or observed in the field. This included both quantitative and qualitative data.

Forest road data collection is time consuming and also expensive. One of the objectives of the thesis was to develop a method to reduce the amount of the fieldwork needed for forest road data collection and risk assessment. As described in Chapter 7, predicting the hydrologic distance between roads and streams using GIS techniques is one of the methods, which can reduce the amount of the fieldwork.

The most important variables influencing the rill and gully occurrence on road surface and at the outlet of drainage structures, and road-to-stream connectivity, were identified from first principles and tested using GIS techniques and logistic regression analysis. These important variables were then used to develop a 'Forest Road Impact Assessment' (FRIA)

[1] In this thesis, "roads" refers to typical roads servicing Australian plantation forests. These can include sealed roads, but are typically unsealed roads, often with native surface, and tracks.

method which is of practical use to forest managers. This method uses the spatial attributes of the drainage structures and terrain attributes to predict the probability that sediment from a forest road will affect the water quality of an adjacent stream.

The integrated risk to water quality arising from the unsealed forest roads was then mapped to identify the locations of the roading system at higher risk, or for which management for risk mitigation is relevant.

1.3 Thesis Organization

The chapters of the thesis are organised into four main parts: (1) introduction and literature review; (2) description of the study area, methodology and data sets; (3) results and discussion; and (4) summary and conclusion (see Table 1.1).

Table 1.1. The structure of the thesis

Parts		Chapters	
1	Introduction and literature review	1	Why Forest Roads and Water Quality?
		2	Assessing the Risks of Soil Erosion From Forest Roads: A Review of the Literature
2	Description of study area, methodology and data sets	3	Description of Case Study Area
		4	Methodology and Data Sets
3	Results and discussion	5	Results and Discussion1: Estimating Relative Soil Erosion Using the Revised Universal Soil Loss Equation (RUSLE) and GIS Techniques
		6	Results and Discussion 2: Digital Terrain Modelling and Development of Rill and Gully Occurrence Risk Models
		7	Results and Discussion 3: Predicting the Probability and Risk of Road-to-Stream Connectivity
4	Summary and conclusion	8	Conclusions and Implications

An introduction is presented in chapter one. A literature review to establish the context of the study in relation to soil erosion, water quality impacts, terrain attributes, risk assessment, forest road technical information, and assessment of the risk in forest roads is presented in Chapter 2. Characteristics of the study area are described in Chapter 3. The reasons for selecting the Stromlo forest as a case study area, and characteristics of soil and climate and forest road network, are also presented in that chapter. A detailed explanation of the methodology used in this study is presented in Chapter 4, while discussing the experimental approach, design and sampling strategy; terrain modelling and analysis; forest roads and hydrological analyses; development of rill and gully occurrence and road-to-stream connectivity models and risk assessment and mapping.

The results of the study are discussed in Chapters 5, 6, and 7. In Chapter 5, the use of RUSLE for predicting and mapping the potential distribution of soil loss on the catchment area and forest roads is explained. The way in which the related factors can be calculated and then combined for presenting final outputs is also described. Furthermore, the details of how GIS techniques are used to calculate and draw the risk map for potential soil loss are presented here.

In Chapter 6, the results of DTM, the characteristics of all the variables – the field recorded data and terrain attributes – used in this study, and the results of model development using statistical analysis are explained. The processes and results of using the 'development' data set to build predictive models for the probability of rill or gully erosion occurrence on the road surface and at the outlets of the road drainage structures, and the testing and validation of the models using a 'validation' data set, are also described.

Chapter 7 discusses the results of slope position and landform classification analyses, forest road analysis, watershed delineation and modelling the hydrologic distance between roads and streams using GIS–based modelling. The hydrologic distance predicted by GIS modelling and the distance measured from the field are then compared. The prediction of road–to–stream connectivity using a fitted threshold curve, modelling the probability of connectivity, and the risk map of road–to–stream connectivity are also presented.

Finally, Chapter 8 concludes the thesis by describing the Forest Road Impact Assessment (FRIA) framework and presenting a final risk map of the forest road network of the study area. The method integrates the different approaches presented in Chapters 5, 6, and 7. The benefits of applying the method for assessing the risk arising from the forest roads on the elements at risk, and recommendations for future work, are then discussed.

Chapter 2
Assessing the Risks of Soil Erosion from Forest Roads: A Review of the Literature

2.1 Introduction

To plan the construction of new roads or to manage existing roads, it is necessary to understand to the processes of soil-water interaction and the likelihood of impacts of forest roads and transportation activities on environmental values. Forest roads are essential for conducting forest and land management activities, transporting forest products, fighting fires, and providing access for recreation. However, roads also cause environmental problems, including increased surface runoff and soil erosion, which can lead to degradation of water quality in adjacent streams (Montgomery and Dietrich, 1988, 1992; Montgomery, 1994; Croke *et al.*, 1999; Croke and Mockler, 2001). An increasing body of scientific knowledge related to these problems has accumulated, particularly over the last two decades.

When the natural rate of erosion from landscapes is compared with that from managed forests, it is found that even the lowest soil erosion rate associated with forestry activities is 2.5 times higher than the natural geologic rate of soil erosion. Sediment production from forest road systems may account for about 50 to 60 percent of the total sediment production from all forest activities (Elliot *et al.*, 1994).

Logging roads or snig tracks are usually the main sources of environmentally damaging runoff and soil erosion problems. When logging and extraction roads are formed without cross-banks and outsloping, the runoff can flow and concentrate on the surface of the road and this will cause serious surface erosion. Haupt (1959), however, noted that even logging roads with adequate mitigation facilities like cross ditches, dips, and outsloping could still contribute significant sediment because of runoff concentrated on the fill batter. Water quality and quantity impacts can be directly related to soil erosion derived from forest road construction and maintenance activities, vehicle movements, and road wear.

This chapter is divided into three different sections: risk assessment and management, soil erosion and water quality, and terrain attributes. The first section discusses assessment and management of risk. This analysis of the issues provides the technical background to the discussion of forest roads and their effects on the soil and water (see Chapters 4, 6 and 7). The second section reviews the basic and natural phenomena of soil erosion, and water quality impact mechanisms and processes. The last section discusses terrain attributes such as slope, aspect, Compound Topographic Index (CTI) or Topographic Wetness Index (TWI) and Stream Power Index (SPI).

2.2 Risk Assessment and Management

2.2.1 Overview

Risk assessment and risk management are important tools and processes in environmental management systems, especially the management of forest roads. The past three decades have seen a dramatic increase in the consideration of risk and uncertainty within the context of environmental management systems. One of the most important principles of an environmentally sustainable management system is that the values of soil and water as well as other environmental values must be protected. Impacts caused by forest road formation and timber harvesting systems are the major environmental risks arising from forest management activities.

Risk assessment is defined as a formal procedure for qualifying risk with regard to the damage potential (Gadow, 2001). In practice, risk assessment measures two elements of the risk; the likelihood that the loss will occur, and the magnitude of the consequences and/or potential loss (Beer and Ziolkowski, 1995; Gadow, 2001). It also requires identifying what hazards exist in an area, and how likely these hazards are to cause harm to the elements at risk. There are various approaches to assessing the level of risk. These approaches range from a quantitative model to a purely qualitative approach. However, all approaches involve making judgements about how acceptable a risk is (Gadow, 2001; UNISON, 2005).

The History of Risk and Risk Management Development

For more than 250 years, the notion of risk has been a basic component of management systems. Daniel Bernoulli (1738) set the foundation stone of neoclassical economics through his development of the concept of choice under risk and uncertainty. Although Bernoulli's concept concerned gambling and the theory of games, the idea of risk and uncertainty became relevant and important for economic and management analysis in the 20th century, when it was re-introduced by Knight (1921) based on Bernoulli's idea (all cited in NEDSTATBASIC, 2001). Prior to Knight's work, Menger (1871), Fisher (1906) and Edgeworth (1908) had expressed the idea that risk and uncertainty should be incorporated into economic theory (all cited in NEDSTATBASIC, 2001). After Knight, many economists applied the concepts of risk and uncertainty to explain investment and economic decision making, profit forecasting, financing, the size and structure of firms, production flexibility, management decisions and the rational foundation for decision-making (Chyruk, 2000).

Risk assessment has become one of the tools in environmental science worldwide during the last three decades. Environmental risk assessment generally deals with the probability of an event causing a potentially undesirable effect (Beer and Ziolkowski, 1995). The most commonly discussed means of addressing risk in environmental sciences is assessment using qualitative risk assessment. Assessing the risk and considering uncertainty in management systems will help managers and decision-makers make more informed and accurate decisions and will also help ensure more successful management outcomes.

The idea of risk assessment in the context of management is new in forestry, especially in forest road management systems. Scientists have used risk assessment for managing and evaluating the effects of insects, diseases and wind on forest stands since the 1960s. Assessing the risk of forestry activities and deforestation on changing behaviour, migration, population and distribution of wildlife, pollution, climate changes, fire, drought, frost, flood, soil erosion, and land slides has been common in environmental studies in recent years. The development of modern technologies, including computing and software, makes the application of the risk assessment faster. For example, Chen *et al.* (2001) developed a Geographic Information Systems (GIS)-based risk decision-making system for natural hazard assessment called Multi-Criteria Evaluation (MCE). MCE generally combines a set of criteria or GIS layers to create a single composite for a decision (Carver, 1991; Buckley, 1984; IDRISI, 2004).

2.2.2 The Benefits of Assessing Risks

Managers and decision-makers seek to have effective management systems in place for their areas of responsibility. Each management decision contains some risk, and sometimes it will be difficult to control all the effects of risk. Every manager or decision-maker is concerned about uncertainty and the likelihood of failure. The assessment and management of risk are therefore normal in management systems.

Risk assessment generally provides an input to decisions about whether risks need to be treated, and identifies the most appropriate and cost-effective strategies (AS/NZS, 2004). However, controlling and reviewing the elements of risk in a management system does not mean that risk can be avoided completely; it means that risk can be managed and minimised to some extent. Some of the important benefits of assessing and managing risk are (Norton *et al.*, 1995; Rose, 1998; Dieter *et al.*, 2001; Gadow, 2001; QAS, 2002; AS/NZS, 2004):

- Improved resource management systems;
- Improved accuracy of management practices and more effective management application;
- Provision of a systematic approach to decision making in management systems;
- Reduction of uncertainty in management systems;
- Improved safety of management;
- Reduction in the number of high cost events in management practice, especially in forest management systems;
- Provision of more effective strategic planning in management systems to achieve aims;
- Better utilisation of resources, especially natural resources;

- Providing informed decisions and ensuring more successful outcomes.

2.2.3 Definitions

There are many definitions of risk and uncertainty, and a single definition of risk is generally insufficient. **Risk** arises out of uncertainty and refers to the occurrence of undesirable and uncontrollable outcomes (Government of NSW, 2000). "Risk has been defined as the expected loss due to a particular hazard for a given area and reference period" (Gadow, 2001:v). A general formula for calculating the probability of risk is:

$$p = R/s \qquad (2.1)$$

where p is the probability, R is the expected loss, and s is the damage. The Australian and New Zealand Standard 4360 (AS/NZS, 1999) defines risk as the chance of something happening that will have an impact upon objectives. However, it is clear that when risk is connected with decisions, it has to be distinguished from danger (QAS, 2002). Risk has two main elements: likelihood and consequences. In decision theory, risk means uncertainty and risk analysis aims at minimizing the failure and impacts to achieve a desired result and decision (PCW, 2002). According to the QAS (2002) and AS/NZS (1999) the term **danger** is defined as liability or exposure to harm or injury.

Boyer *et al.* (1999:3) define **Consequences:** "consequences are a combination of the elements at risk and the severity and /or frequency of the event on those elements at risk". In addition, consequences can also be defined as the effect of a potential event on elements at risk or the outcomes of an event that will be expressed qualitatively and quantitatively, being a loss and an injury (Boyer *et al.*, 1999; QAS, 2002). **Likelihood** is the description of probability and frequency. The term likelihood is used in qualitative analysis and it "relates to how likely it is that something will occur" (QAS, 2002:43).

According to Greenfield (NASA, 1998) and QAS (2002), **uncertainty** refers to the implications of lack of knowledge and information or understanding of the possible outcomes, which must be taken into account as a variable when evaluating risk. In *Quality Assurance Services* (2002:83), risk and uncertainty are divided into four levels: "Risk-where we do know the odds; Uncertainty-where we do not know the odds but may know the parameters; Ignorance- where we 'do not know what we do not know'; and Indeterminacy- where the causal chain of events is open".

Tolerability is the willingness to live with the effects or the ability to suffer hardship of a problem with a particular risk without being harmed or damaged in order to secure benefits. Tolerability does not mean acceptability, but the consequences can be properly controlled or endured; we need to keep it under review in order to reduce risk and its consequences (QAS, 2002). The term '**acceptable level of risk**' implies that risk has been accepted and qualified and that a decision has been taken that the likely unfavourable outcomes are not sufficiently bad to stop the plan of action. In addition, further consideration or treatment cannot reduce the impacts of the level of risk any more without further investment.

Risk Assessment is the scientific process of asking how risky something is (Friedman, 1994; QAS, 2002). Risk assessment can be defined as a process of collecting and analysing data in a specific area for identifying the problems and the ways of reducing the impacts of risk. The main objectives of risk assessment are, then understanding the nature of risks, identifying risks and acting to control the impacts of risks (Boehm, 1989; QAS, 2002).

Risk Management is thus an organised and systematic decision-making process that efficiently identifies risks, assesses or analyses risks and effectively reduces or eliminates risks to achieving program goals (AS/NZS, 1999). According to the Australian and New Zealand Standards 4360 (AS/NZS, 1999) risk management can also be defined as the culture, processes and structures that are directed towards the effective management of potential opportunities and adverse effects. Risk management systems will, however, be complicated, especially in environmental management systems, because of the uncertain nature of the risk.

2.2.4 Risk Assessment in Forestry

Today, risk assessment and management are common in forest management systems: "a forest enterprise manager runs risks, when deciding harvesting strategies" (Dieter *et al.*, 2001:201). Assessing and predicting, then managing risks and uncertainty, are part of normal forest management systems.

For example, forest fire risk assessment has become one of the most used forest risk tools worldwide, to identify and assess the probability of fire occurrence and level of risk associated with the fire. There are a variety of existing fire risk assessment and mapping methods, especially in Australia, Canada, and America, where bushfires are frequent. Blanchi *et al.* (2002) developed a methodological approach for forest fire risk assessment to clarify the concepts relating to this risk, to appreciate the multiplicity of existing needs, to analyse the means of risk assessment and to identify the data currently usable, as well as the processing and the information systems available.

Risk assessment processes have also been applied to forest road management systems. For example, USDA Forest Service (2003) developed a risk assessment process to compare the benefits of the road system with the impacts or risks that the roads pose to key resources. Yoshimura and Kanzaki (1998) developed an expert system for automatically laying out a forest road, based on the risk assessment of slope failure. The advantage of this method is that the decision about where to locate forest roads can be automated (Yoshimura and Kanzaki, 1998).

2.2.5 The Process of Assessing and Managing Risk

Generally, risk management has two primary steps: risk assessment and risk control. Risk assessment can be divided into three different steps: risk identification, risk analysis, and risk prioritisation (Boehm, 1989; Rose, 1998). Risk assessment is an important step in risk management, because most management decisions and procedures for risk control will follow on from the results of a risk assessment. Risk control also involves three steps: risk management planning, risk resolution and risk monitoring (Boehm, 1989). According to Boehm (1989), a risk analysis will produce a performance and assessment model of the loss probability, cost models, network analysis, and decision-making analysis.

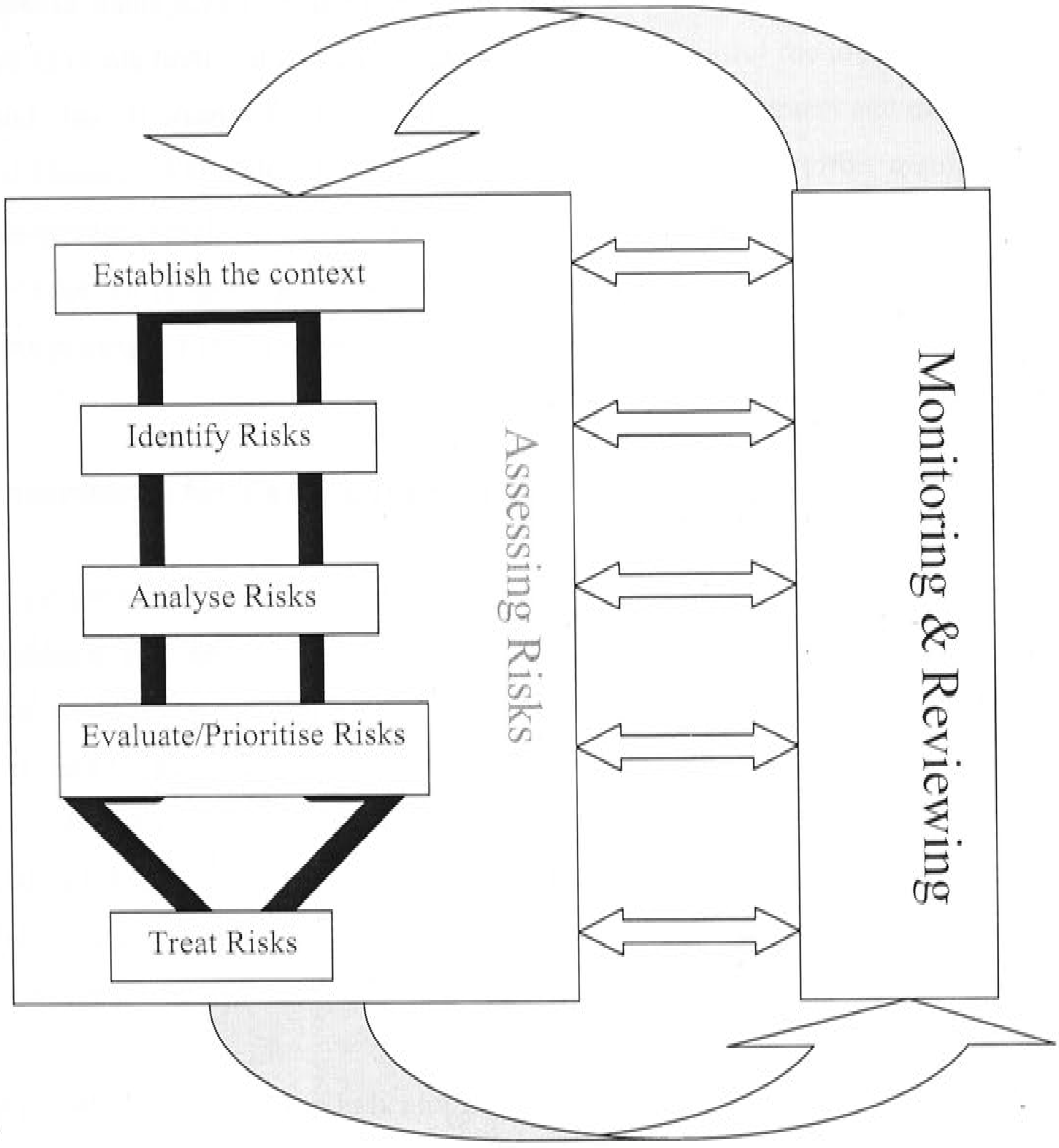


Figure 2.1. Risk assessment and management processes
Source: Reproduced from AS/NZS (1999)

According to the *NASA Procedures and Guidelines* (1998), risk management processes and functions involve: identifying risk issues and concerns; analysing, evaluating, classifying, and prioritising risks; risk decision-making and planning; and risk tracking and controlling.

The main elements of the risk assessment process are: establish the context; identify risks; analyse risks; and evaluate and prioritise risks (Rose, 1998; AS/NZS, 1999). These processes are illustrated in Figure 2.1.

Risk has always been of great concern in management systems, especially in natural resource management. Many forest managers have viewed risk as something to be avoided and have required a specific program to review and control the areas at risk. On the other hand, there is no specific or standard approach for risk assessment and management (Moore and Hamm, 2000). Therefore, a successful risk management effort requires an individual management responsibility for each risk program. A good risk management decision and management program requires "a focus on evaluating [and] prioritising hazard reductions or responses to risks" (Moore and Hamm, 2000:3).

Procedures for Assessing Risk in Forest Road Systems

In the context of this thesis, risk assessment in forest roads is a process that evaluates the likelihood that adverse environmental impacts on water quality may occur as a result of road construction and use. One of the main environmental problems of forest road systems is related to the high sediment delivery from roads to streams. Generally, most forest roads are not sealed with a waterproof surface and tend to concentrate water flow. The main result of this is the increased delivery of eroded sediment to streams. Locating the source and assessing the severity, probability and frequency of such risks occurring must be part of forest road systems research methodology.

Geomorphology can be an indicator in the assessment of road hazards and in controlling the harmful impacts caused by forest roads. Slope gradient, length and position of road, stream channel proximity and road-to-stream connectivity, soil and bedrock geology, road density, stream crossings, upslope contribution area and road contribution area of runoff delivery to road drainage structures can all be indicators of the risks to road related water quality impacts (Rice and Lewis, 1991; Montgomery, 1994; Wemple *et al.*, 1996; Croke and Mockler, 2001; Takken *et al.*, 2005). These indicators can answer the following basic questions related to risk assessment in forest road systems: how, when and where do the forest road systems generate surface erosion?; how and where are the forest road systems hydrologically connected to the watercourses?; and how, when and where do the forest road systems affect water quality and quantity? However, according to USDA (1999, 2004), indicators alone cannot answer these questions; they should be chosen, applied and used only in the context of understanding how forest road systems can affect watershed processes and water quality impacts.

It will be argued in this thesis that understanding the elements at risk – soil and water quality – in forest road systems, for a particular location or road segment, is the first step in assessing risk. Risk assessment involves consideration of the sources of risk, their consequences and the likelihood that these consequences may occur. Risk assessment can be qualitative, semi-qualitative, or quantitative, or a combination of these, depending on the circumstances (NASA, 1998; AS HB 203, 2000). The most common risk analysis used in environmental sciences is qualitative (Beer and Ziolkowski, 1995). Beer and Ziolkowski (1995), and Ryan *et al.* (1998) used a qualitative risk analysis to assess soil erosion hazards for Australian forest management.

Qualitative analysis uses descriptive scales to describe the magnitude of potential consequences and the likelihood that those will occur. Villeponteaux and Elder (2000) used a qualitative risk assessment called 'crossing inventory and assessment' to identify the risks of road-stream crossing pose to aquatic resources, especially sedimentation of anadromous fish habitat. Villeponteaux and Elder (2000) stated that the probability of risk associated with the site – the road-stream crossing point – is the combination of two major elements: pipe capacity and upslope debris flow hazard, as well as a lesser component. Consequences of failure are composed of four unequally weighted factors – fill volume, diversion potential, potential debris flow generation and volume of the flow (Villeponteaux and Elder, 2000). Essential data for both non-stream and stream crossing roads were then collected from the field using GPS. These were used in conjunction with available GIS layers to identify the problem areas in each sub-watershed (Villeponteaux and Elder, 2000).

As discussed above, the first step in risk assessment is to establish the context, and identify the risk issues and concerns that need to be managed. Approaches used to identify risks can include any combination of checklists, judgments based on experience and records, flow charts, 'brainstorming' meetings, systems analysis, scenario analysis, and systems modelling (NASA, 1998; AS/NZS, 1999; QAS, 2002). Risk analysis, evaluation, and classification are the next steps to determine the level of a risk. The analysis process should be defined and structured prior to the risk level estimation, which should use explicit scales for the likelihood and consequences.

Establishing the Risk Criteria

In practice, an important component of risk assessment is finding those risks which are most critical, and providing a methodology to assess their potential impacts. For example, Garvey (1998) argued that a 'risk matrix' is one approach for identifying, assessing, and ranking program risks. Garvey (1998) also believed that risk raises the possibility that a program's requirement may not be achieved by available technology or reliable engineering procedures. A risk matrix study can include such elements as identifying and describing the risk, the probability of risk occurrence, and assessing the impact of the risk. In this regard, Garvey (1998) introduced criteria for the probability of risk occurrence, the consequences of the risk, and risk rating (Tables 2.1-2.3).

Table 2.1. Probability of occurrence: Illustrative Interpretations

Probability Range	Interpretation
0-10% (Rare)	Very Unlikely to Occur
11-40% (Unlikely)	Unlikely to Occur
41-60% (Possible/Moderate)	May Occur About Half of the Time
61-90% (Likely)	Likely to Occur
91-100% (Almost certain)	Very Likely to Occur

Source: Adapted from Garvey (1998)

Table 2.2. Illustrative definitions of impact (consequences)

Impact/consequences Category	Definition
Catastrophic (C)	An event that, if it occurred, would cause program failure (inability to achieve minimum acceptable requirements).
Major (M)	An event that, if it occurred, would cause major cost/schedule increases. Secondary requirements may not be achieved.
Moderate (Mo)	An event that, if it occurred, would cause moderate cost/schedule increases, but important requirements would still be met.
Low (L)	An event that, if it occurred, would cause only small cost/schedule increases. Requirements would still be achieved.
Insignificant or Negligible (N)	An event that, if it occurred, would have no effect on the program.

Source: Adapted from Garvey (1998)

Table 2.3. A risk matrix: possible risk rating scale

Impact Category / Probability Range	Negligible	Minor	Moderate	Major	Catastrophic
0-10%	Low	Low	Low	Medium	Medium
11-40%	Low	Low	Medium	Medium	High
41-60%	Low	Medium	Medium	Medium	High
61-90%	Medium	Medium	Medium	Medium	High
91-100%	Medium	High	High	High	High

Source: Adapted from Garvey (1998)

In the case of forests, one risk is that associated with sheet erosion. Sheet erosion is generally a slow process and difficult to recognise, but it becomes faster and clearer on steep terrain. This type of erosion is common in managed forests, especially in harvested areas and on forest roads (Zachar, 1982). Zachar (1982) defined criteria for sheet erosion classification to evaluate and rank the level of risk associated with the intensity of soil removal (Table 2.4).

Table 2.4. Criteria for sheet erosion classification based on the intensity of soil removal

Intensity of soil removal (m^3/ha/year)	Assessment Description	Class (Risk ranking)
<0.5	No erosion (nil)	Negligible
0.5-5	Slight erosion	Low
5-15	Moderate erosion	Moderate
15-50	Severe erosion	High
50-200	Very severe erosion	Very high
>200	Catastrophic erosion	Extreme

Source: Adapted from Zachar (1982)

Table 2.5. Criteria for potential sediment delivery from road surface erosion sources

Class	Rating	Road, logging trail and ditch line erosion	Non-specific surface erosion sources
VL	Very low	Road, logging trail or ditch lines crossing the unit will not provide a direct avenue for sediment into any ephemeral or permanent stream.	The terrain unit is separated from any ephemeral or permanent stream by at least 20 m of gently sloping, well-vegetated ground.
L	Low	Road, logging trail or ditch lines crossing the unit will provide a direct avenue for sediment into any ephemeral stream, which crosses ≥ 200 m of gently sloping terrain before it reaches a permanent stream.	Sediment source on a gully sidewall or stream escarpment leads directly into an ephemeral stream, which crosses ≥ 200 m of gently sloping terrain before it reaches a permanent stream.
M	Moderate	Road, logging trail or ditch lines crossing the unit will provide a direct avenue for sediment into any ephemeral stream, which crosses 100 -200 m of gently sloping terrain before it reaches a permanent stream.	Sediment source on a gully sidewall or stream escarpment leads directly into an ephemeral stream, which crosses 100 - 200 m of gently sloping terrain before it reaches a permanent stream.
H	High	Road, logging trail or ditch lines crossing the unit will provide a direct avenue for sediment into any ephemeral stream, which crosses < 100 m of gently sloping terrain before it reaches a permanent stream.	Sediment source on a gully sidewall or stream escarpment leads directly into an ephemeral stream, which crosses < 100 m of gently sloping terrain before it reaches a permanent stream.
VH	Very high	Road, logging trail or ditch lines crossing the unit will provide a direct avenue for sediment into a permanent stream.	Sediment source on a gully sidewall or stream escarpment leads directly into a permanent stream.

Source: British Columbia Environment (1995a)

British Columbia Environment (1995a) defined criteria for potential sediment delivery from road surface erosion to the adjacent streams (Table 2.5). These criteria describe the type of sources (that is, road, logging trail and ditch) and their condition on the ground, and the level of risk rating assigned. As can be seen from the table, when roads and logging trails are located far away enough (>200 m) from a stream line, the sediment delivery risk will be very low to low. Risk probability can therefore be ranked according to the certainty of sediment production from the total forest road prism and the degree of road-to-stream connectivity.

Risk Acceptability

In many risk assessments, it may be necessary to determine the level of acceptable risk during the assessment processes. This is the case for forest road risk assessment. However, the precision of the risk acceptability criteria may vary with the objectives of the risk assessment (Kasperson and Kasperson, 1983; AS/NZS, 1999). There is no zero risk situation in forest road risk assessment; all decisions or situations involve some level of risk, though the risk can be very low. Extreme risk is generally an intolerable risk level and is unacceptable (AS/NZS, 1999). The vast majority of risk assessors accept negligible and very low risks as acceptable risk levels. However, the particular risk acceptability depends on the particular case under consideration.

Creating a Risk Map

Risk mapping is a technique used to help present identified risks and determine what actions should be taken toward those risks (Bouma and van Groenigen, 1995; Akcakaya, 1996). As mentioned above, the possible risk occurrences can be ranked, based on their relative relationship to the possible consequences and the possible likelihood of an occurrence, using a risk matrix. Mapping a risk occurrence generally aims to subdivide an area or a road into different risk intensities due to the function of factors influencing the risk and the evaluated level of risk. Understanding the exact extent of a specific risk to the elements at risk, by mapping the risk factors and how they might change in the future, is vital to planning for development and controlling the risk (Bouma and van Groenigen, 1995; Christakos *et al.*, 2001). One technique that has proven most effective in providing this desired perspective is using GIS as a primary tool to map assessed risk (Akcakaya, 1996). The risk map will quickly and effectively provide the managers with a view of a risk, thus assisting them to treat and control the risk.

GIS is being used increasingly in forestry for purposes such as mapping, planning, managing the forest and forest operations, characterising the distribution of fire and disease hazards, and creating erosion and flood risk maps (Chuvieco and Salas, 1996; Christakos, 2001). One of the most frequently used methods for mapping a risk distribution of a GIS raster layer is the pixel-based approach. This pixel-based approach utilizes the spatial information of the pixels to classify the raster (Yan, 2003).

The risk level of each factor can be ranked using a risk matrix to create a risk component. Each risk component may include several factors influencing the risks associated with the elements at risk. The aggregate risk scores for each pixel can be determined by summing the risk score of each of the variable for each pixel. The GIS overlay application can then be used to classify, combine and map the ranked risk components.

2.3 Soil Erosion and its Water Quality Impacts

2.3.1 Overview

Soil erosion related to agricultural and forestry activities is one of the most critical problems facing land managers. Table 2.6 shows the causes of soil degradation in the world, with overgrazing (35%), deforestation (30%) and farming (28%) being the main causes.

Table 2.6. Causes of soil degradation in the world by region (by percentage)

Area	Agriculture	Deforestation	Fuel wood	Overgrazing	Industrialisation
Africa	24	14	13	49	-
Asia	27	40	6	26	-
Central America	45	22	18	15	-
Europe	29	38	-	23	9
North America	66	4	-	30	-
Oceania	8	12	-	80	-
South America	26	41	5	28	-
World	28	30	7	35	1

Source: Adapted from WRI (1990); Oldeman *et al.* (1990)

The general concepts of soil erosion have been discussed by FAO (1965), Oldeman *et al.* (1990), Elliot *et al.* (1994) and El-Swaify (1997). Erosion processes have been discussed by Zachar (1982), Cabrido (1985), James and Russell (1993:3) and Misra and Teixeira (2001). Although most erosion research has focused on agricultural lands, quantitative studies of forest soil erosion began about 1915-1917, by the U.S Forest Service, and much research since 1975 has considered the impacts of soil erosion associated with unpaved forest roads (Ziegler *et al.*, 2001).

2.3.2 Classification and Types of Soil Erosion

Soil erosion is generally classified into two main categories – geological and accelerated erosion. Geological erosion is a natural, normal and slow process that occurs over long geological periods. It also represents erosion of land in its natural environment without human influence or interference and includes soil forming as well as eroding processes (FAO, 1965). Accelerated erosion occurs much more rapidly than geological erosion and is caused by human and animal activities (Agriculture and Agri-food Canada, 1996). Most erosion problems are related to accelerated erosion. The erosive agents can be classified into wind, water and ice and snow erosion. This research is only concerned with water erosion. Soil erosion caused by the action of water can be divided into five categories: splash or raindrop erosion, sheet erosion, rill erosion, gully erosion and, finally, stream or channel formation (Figure 2.2). The physical process of erosion and the factors related to each part of the process are explained in the following sections.

Splash Erosion

Splash or raindrop erosion occurs when the rain strikes the ground or the surface of the soil directly and the soil structure collapses under the force of the raindrops. Soil particles generally break down into finer particles by raindrop action and simplify other stages of the erosion process like transportation.

Sheet Erosion

Sheet erosion, which is also known as surface erosion, is one of the most common erosion types in agricultural land and also on bare and gently sloping land. The soil becomes saturated after long intensive rainfall and then the water moves easily on the surface of the soil.

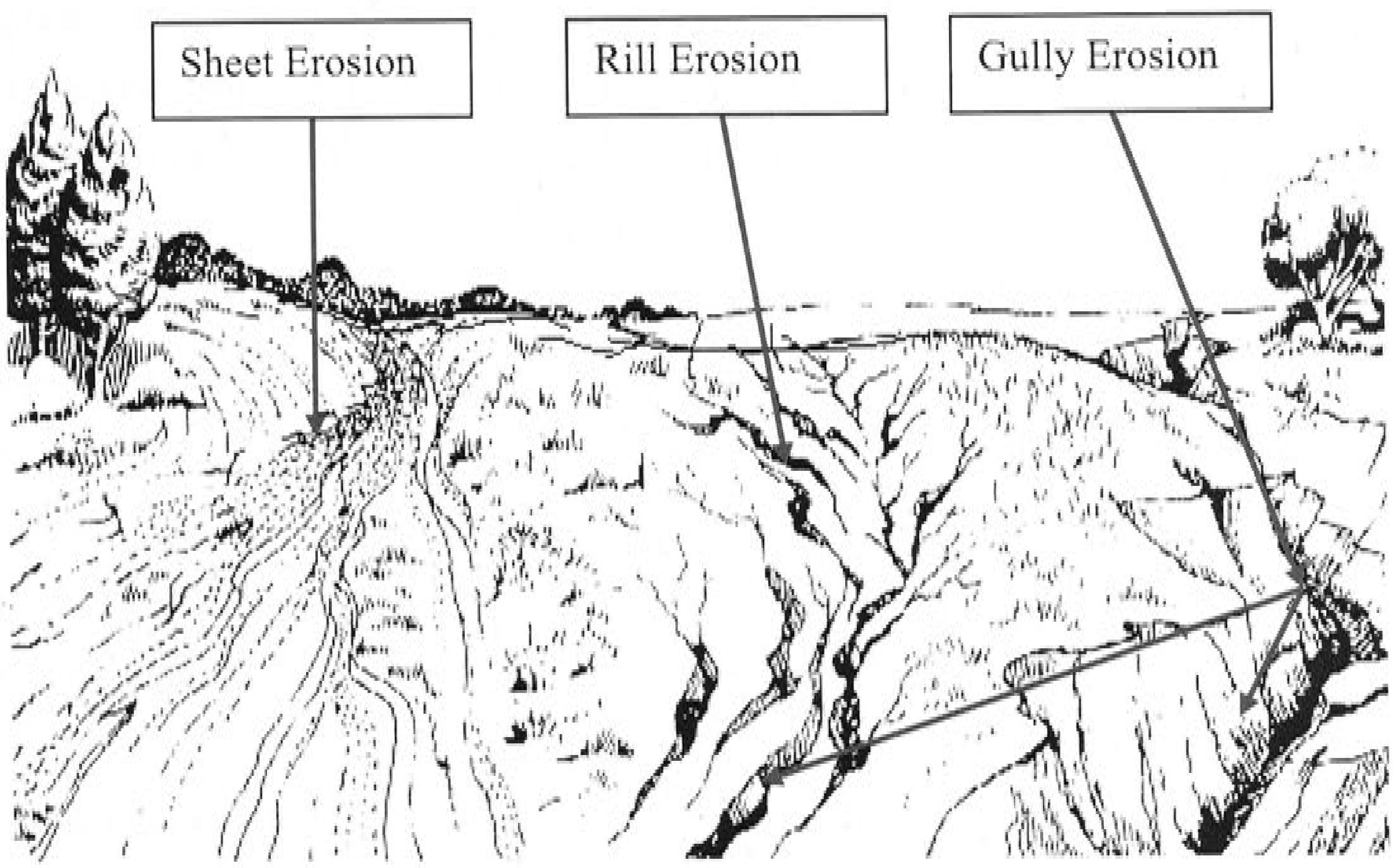


Figure 2.2. Different types of soil erosion by runoff and water movement downhill
Source: Adapted from Matchett and Moyer (2000)

Rill Erosion

Sheet and rill erosion are two types of land and soil degradation resulting from the action of water and runoff. Rill erosion is the removal of the top layers of soil from sloping and recently cultivated land, creating small channels. A rill has also been defined as the process in which many small channels up to 30 cm deep are formed (Agriculture and Agri-Food of Canada, 1996). Rill erosion is one of the most common erosion processes in hillslopes and un-maintained forest road systems. Rill erosion generally occurs on the surface of the roads because of the lack of drainage structures and/or poor maintenance. It also occurs at the outlet of drains (culverts, mitre drains and cross drains) due to the highly concentrated water flow and slope.

Gully Erosion

Gully erosion has become an important topic of research since the 1980s. Gully erosion is the removal of soil from narrow channels (for example, rills) to various depths by concentrated runoff. Gully systems discharge polluted water, sediment and also debris from upland into streams. Forestry operations such as timber harvesting and road construction can increase gully erosion. According to Agriculture and Agri-Food of Canada (1996), the depth of a gully can vary from around 30cm (1ft) to 30 metres (100ft). The gully erosion process occurs faster in steep terrain where the potential soil erosion (detachment and transport) and runoff force are higher than in other areas. The size of the channel or gully depends mostly on the soil type, detachability and transportability of soil, contribution area or size of the catchment, the volume of runoff (concentrated water), slope steepness and slope length. According to the British Columbia Ministry of Forests (2001), gully erosion will occur when slope steepness and the overall channel gradient is equal or greater than 25%.

Human activities can increase the likelihood of gullies occurring, especially on unstable land with weak soil structure and strength. Gully erosion is the worst stage of soil erosion and sometimes the area cannot be restored. In forestry operations, gully erosion is more likely to occur after timber harvesting and road construction.

Table 2.7. Classification of gully erosion rate by longitudinal growth

Growth of erosion gullies (metres/year)	Assessment Description	Class (Risk ranking)
< 0.5	Erosion nil	Negligible
0.5-1.0	Slight erosion	Low
1.0-3.0	Moderate erosion	Moderate
3.0-5.0	Severe erosion	High
5.0-10.0	Very Severe erosion	Very high
>10.0	Catastrophic erosion	Extreme

Source: Adapted from Zachar (1982)

Table 2.7 shows that the risk of gully erosion is low to negligible where the rate of growth in gully length is less than 1 metre per year. The reason for this is that the size of the extension (growth rate) cannot provide enough material for transportation and deposition. The worst problems of sedimentation occur where the gully length growth is more than 1 metre per year, but they can be controlled and recovered when this rate is less than 5 metres per year (classes low to high). However, it is sometimes impossible to control or restore areas in classes very high and extreme, because of the severity of the effects and the continuous nature of the processes.

Table 2.8. Classification of gully erosion by total gully length

Total length of erosion gullies (km/km^2)	Assessment Description	Class (Risk ranking)
< 0.1	Erosion nil	Negligible
0.1-0.5	Slight erosion	Low
0.5-1.0	Moderate erosion	Moderate
1.0-2.2.0	Severe erosion	High
2.2.0-3.0	Very Severe erosion	Very high
>3.0	Catastrophic erosion	Extreme

Source: Adapted from Bucko and Mazurova (1958); cited in Zachar (1982)

As can be seen from Table 2.8, the risk of gully erosion is negligible where the length of the gully is less than 100 metres per square kilometre (km^2). This gully process is natural; under the influence of natural factors it could be ignored. The most critical problems of gully erosion occur where its length is more that 2 km per km^2 (very severe and catastrophic erosion events). The effects of this degree of gully erosion are problematic, uncontrollable, and irrecoverable in both agriculture and forestry management systems. Controlling and managing the factors influencing and affecting the gully erosion processes (causes) in these classes before they occur is the best way to reduce the impacts of erosion.

Bank Erosion and Channel Formation

Bank erosion, which is also called channel formation, is a common erosion process in channel and stream network systems where there is no vegetation protection on the channel sides or channel stability. Hauge (1977:203) defined stream bank erosion as "erosion in which material on or composing the banks of the stream falls into the stream and is removed by flowing water; removal of materials deposited in streams by landslides or other mass movements".

2.3.3 Soil Erosion and Water Quality Impacts from Forest Roads

Almost all human activities speed up the erosion process. The influence of timber harvesting and road construction in forest management areas also has this consequence because the removal of the forest canopy changes the rate of soil infiltration. The forest catchment will not be the same as before the intervention, with the rate of runoff, sedimentation, water pollution, flood, channel formation and bank erosion all likely to increase as a result of these changes.

Recent research has established that operations such as timber harvesting and the process of road construction itself are the most important causes of soil erosion and consequent deterioration of water quality in adjacent streams (for example, Anderson *et al.*, 1976; Rice and Lewis, 1991; Adams and Ringer, 1994; Ziegler and Giambellucia, 1997; Croke *et al.*, 1999; Luce and Wemple, 2001; La Marche and Lettenmaier, 2001; Madej, 2001; Ziegler *et al.*, 2001; Takken *et al.*, 2005). Some of the mechanisms linking unsealed roads to reduced water quality are also well known. Generally, non-exposed topsoil is less likely to be eroded than exposed subsoil. However, it is impossible to avoid removing topsoil in road construction. Consequently, most forest road segments are exposed to erosion. For example, the Water Erosion Prediction Project (WEPP) in the Oregon Coast Range, USA, has shown that the amount of runoff and soil erosion increased dramatically due to the reduced capacity of forest roads to absorb surface water compared to undisturbed forest (Tysdal *et al.*, 1999).

When logging occurs, surface erosion is more likely to occur in steep areas than on flatter areas. Timber harvesting and road construction in steeper areas, and roads across steep terrain which are not maintained after logging, are the main sources contributing sediment directly into stream flow. In some terrains, forest practices result in massive landslides and extensive gullying which transfer considerable sediment and pollution directly into stream channels (Madej, 2001).

Suspended sediment also directly affects stream morphology as well as water quality (Golden *et al.*, 1984). Some heavy sediment from forest roads spends most of its time on the stream bottom as a 'bed load'. Bed load sediment can be suspended, rolled, and bounced during periods of peak flow (Golden *et al.*, 1984). Although some suspended sediment is produced through organic debris, the greatest volume is from soil erosion (Golden *et al.*, 1984).

McRobert and Sheridan (2001) argued that road runoff and drainage have the potential to impact aquatic and terrestrial ecosystems through changes to the quality and quantity of water, and to water flowpath. By increasing the area of impervious surface and causing higher peak flow rates in streams, roads will create changes in the volumes of stormwater runoff (McRobert and Sheridan, 2001). Disturbance and washes in the bed and edge soil of streams and changes to a stream's direction result from an increase in water quantity. This process is directly related to water quality impacts and changes to the water flowpath.

The problems of forest road surface erosion have been evaluated in many studies such as those of Burroughs and King (1989), Grace *et al.* (1997). Tysdal *et al.* (1999), Croke and Mockler (2001), Macdonald *et al.* (2001), Megahan *et al.* (2001), and Ziegler *et al.* (2001) Mills (1997) showed that local climate, type of soil, geology, landform, and disturbance to the hillslope and channels caused by road construction will affect sediment production from forest roads. Generally, unpaved roads generate most runoff, especially when storms occur. Such runoff commonly generates sediment yield as high as 10-15 kg/m^2/ year (Macdonald *et al.*, 2001), although this volume is closely related to the amount of rainfall and frequency of storms, and will therefore be different from place to place.

2.3.4 Mechanisms Affecting Soil and Water

The mechanisms affecting soil erosion processes can also affect sediment delivery behaviour and water quality impact processes. For example, Croke *et al.* (1999) and Croke and Mockler (2001) emphasise the importance of the degree of connectivity between sediment source, runoff source, stream and any other watercourses in determining erosion and water quality impacts. Acceleration of the erosion process and transport of the runoff to a stream are related to the volume of runoff and its energy, the slope gradient and length, runoff catchment area and contributing area and soil types. Novotny and Chesters (1989), and State Forests of NSW (1996) argued that overland flow, the filter strip, and channel processing are the three main components in the mechanisms of sediment delivery processes to streams.

2.3.5 Forest Roads and Erosion

Forest roads can be divided into two major sections in terms of slope and direction of water runoff: the insloped and the outsloped sections (Figure 2.3). The surfaces of roads, ditches, cut batters and upslope forests that contribute water (runoff) flows to road prisms are described as the 'insloped' sections of forest roads. The term 'road prism' describes the cross-sectional configuration of a forest road including the travelway, cut and fill batters and roadside table drains (see Figure 2.3).

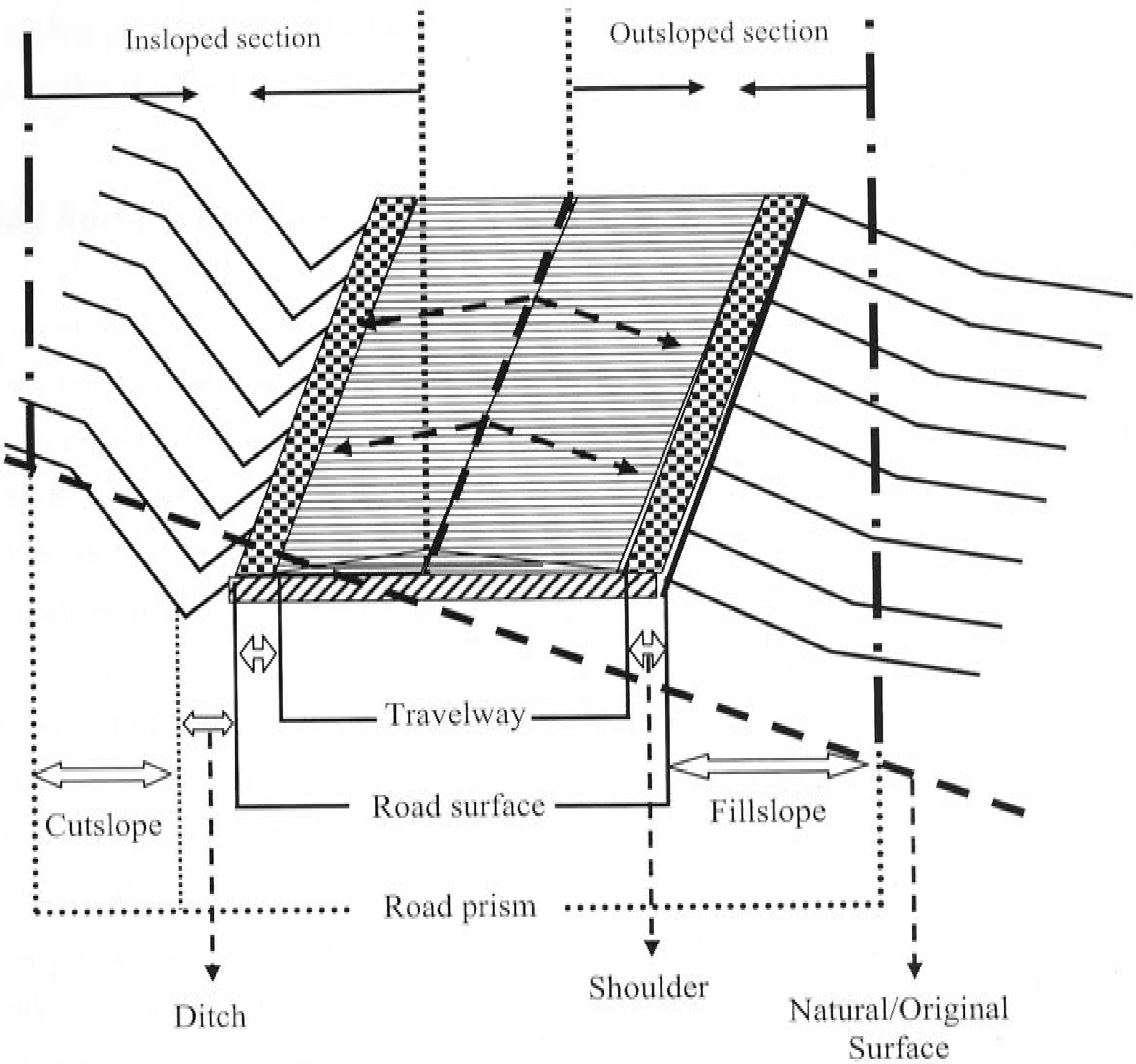


Figure 2.3. Forest road prism and segments

Runoff flows from the surface of the road and cut batter to the ditch, then discharges by drainage structures such as mitre drains, cross-banks and culverts. An 'outsloped' section of roads refers to the segments of roads that let water flow from the road via shoulders and fill batters. The fill batters and parts of the road surface are the main segments of the outsloped road section.

Inslope Road Erosion

There is a strong relationship between discharge of sediment from a ditch and condition of the inslope batter. Furthermore, there is also a strong link between the length of a road segment and the amount of sediment from the ditch that drains it. The road surface itself, cut batters or cutslopes, and table drains are the three main road segments of an insloped road section (Figure 2.3).

Road Surface Erosion

The road surface or travelway provides most of the runoff delivery to the ditch and contributes a significant proportion of the sediment delivery to the stream during the erosion process. The volume of runoff delivered to the ditch is closely related to the amount of rainfall, road contribution area and the slope gradient of the road surface. The effect of the road surface varies according to the type and size of road surface material, the degree of compaction, slope, traffic and the ruts on the road or the degree of surface wear.

The amount of sediment delivered from travelways to ditches or mitre drains depends on the type of road surface, length of the water flow path on the road's surface, and inslope and downslope gradients. Tysdal *et al.* (1999:4) argued that "a rutted road would increase the flow path by diverting the runoff down the ruts for a distance, thus increasing the erosion from the road surface". Burroughs and King (1989) estimated that sediment production from rutted and unsurfaced travelways is increased by a factor of 2 compared to the forested lands. Longer roadslopes can generate higher erosion because of a larger contributing area, but changes in road length do not affect the amount of runoff as much as does contribution area (Tysdal *et al.*, 1999).

The type of road surface materials used can also reduce and/or increase the volume of runoff and erosion. For instance, soil loss and runoff generation from travelways were found to be greatest for silt and clay loam soils, but they were least for sandy loam soils with gravel (Tysdal *et al.*, 1999). However, there are a number of questions still not answered by researchers. For example, where the width of the road is increased, how will the rate of sediment production be changed? What is the effect on sediment production from different types of road surface materials? What is the exact relationship between the contribution length of the road and the rate of sediment delivery to streams?

In this study, it is assumed that rill and gully erosion on the surface of forest roads and at the outlet of drainage structures will have the potential to cause water quality problems, especially where there is a water flow linkage between roads and streams.

Cut Batters

Soil erosion from cutslopes is significant and high during the first few years after road construction, especially when heavy rainfall occurs. This is because the cutslopes are unstable and the soil particles will be easily moved by water down to the ditches. Megahan *et al.* (2001) found a positive correlation between soil erosion from cut batters and rainfall, and modelled total sediment yield for the measurement period of their study. Their model is:

$$\mathrm{Log}_{10}\,E = 0.927^{*}\,\log_{10} R - 0.29^{*}\,\log_{10}(GCD + 0.1) + 1.343^{*}\,\log_{10}(A) + 5.734^{*}\,\log_{10} s - 14.552 + e \qquad (2.2)$$

where E is total sediment yield (tonnes/ha/year), R is total erosivity index (MJ/mm/ha/hour), GCD is ground cover density (percent), A is aspect in degrees, s is slope gradient in percent, and e is an error term with a mean of zero and variance of $\pm$ 0.361 log units. Greater height of cut batter causes more soil erosion and also channel extension because of high runoff generation (Tysdal *et al.*, 1999). As a general rule, where the slope gradient of a cut batter is high and the length of the cut batter within this slope is very long, the erosion hazard will become critical.

Slope failures, mass movements, mudflows and also a high rate of soil erosion are common problems of unstable cut batters in steep terrain during wet seasons and storm events. The problems are more likely to occur during the first few years after road construction, especially during heavy rainfall events. Roads in mountainous forests are more likely to fail because of the height, slope and length of cut batters, on the one hand, and heavy snowfall and rainfall on the other. Cut slope angle, soil type and vegetation cover are the main factors affecting stability of the cutslope against mass movements, slides and erosion processes. Forest road cut and fill batters account for nearly 50 percent of the total road disturbance areas on steep terrains and contribute about 60 percent of the total sediment delivery from forest roads to streams (Grace, 1999).

Roadside Table Drains

Most forest road surfaces are affected by overflowing runoff from roadside table drains and blocked culverts and mitre drains. Although some overflows originate from drain construction problems, they are created mostly by high volume runoff delivery from upslope areas. Consequently, if the road drainage structures cannot successfully clear the runoff, rills or gullies will be created on the surface of the road. The dimension of the rills or gullies is related to the volume, flow-speed, repetition of overflow, the road surface slope (length and width), type of material with which the road has been surfaced and ruts made by vehicles.

Generally, the forest road ditches themselves contribute only a small volume of sediment generated from the road prism. Most sediment delivery from ditch to stream originates from cutslopes and road surfaces. As long as the design of the ditch is adequate, the road attributes and slope gradient are the most important factors of sediment delivery to streams (Croke and Mockler, 2001). Therefore, reduction of sediment production from road surface and cut batter will increase the flow of clean water down the ditch and will decrease sediment delivery from ditch to stream. The rate of sediment generated from ditches depends on channel slope, slope of channel sides, type of bedrock, the techniques used in building the ditch, channel shape, vegetation cover of ditch channel sides and the amount of runoff.

Burroughs and King (1989) argued that the rock blanket treatment for roadside ditches is the most common and effective erosion control treatment. Sediment reduction by gravelling the travelways and ditches and protecting the cut batter has been estimated at 91 percent. The WEPP study on ditches has shown that in all cases the road ditch was being eroded (Elliot *et al.*, 1994; Tysdal *et al.*, 1999). On the other hand, a graded ditch causes more erosion than an undisturbed ditch (Tysdal *et al.*, 1999). Grading both the road surface and the roadside ditches is one of the most common activities in the maintenance of unsealed roads. This is because grading removes ruts and corrects the road surface shape. It also removes obstructions from table drains. However, roads are more likely to be eroded and deliver sediment to streams just after grading, especially when heavy storms occur. The process of grading, while necessary to improve the road surface, disrupts the natural compaction of the road surface.

However, there are no absolute rules for establishing table drain size, shape and slope in roads. Table drain design depends on the environmental and topographic conditions. Cut slope stability is very important to the rate of sediment delivery to streams from ditches. The stability of the cutslope depends on the types of soil and bedrock, construction methods and effective maintenance, natural terrain stability, vegetation cover and slope angle (British Columbia Ministry of Forests, 2002).

Outslope Road Erosion

Shaping the road surface with an appropriate slope in order to keep the road surface dry, is known as outsloping the road. The runoff generally flows slowly from the road surface onto the fill slope then downward to the forest floor. Installing proper mitre drains, push outs, culverts and cross-banks is necessary to reduce the harmful effects of runoff through reducing the speed, volume, velocity of runoff and contribution length of runoff. The road surface and fill batters are the two main road segments involved in outsloping road erosion processes. Drainage structures are another part of this road section but these will be illustrated and explained later.

Although most researchers are concerned about the insloped road erosion problems of forest roads, there are some serious erosion problems occurring in outsloped sections, especially from the fill batter. This is supported by research; for example, the U.S Environmental Protection Agency (EPA, 1975) reported that one of the main problems of outsloped roads is mass movement, and this can increase sediment delivery to streams. The EPA also argued that poor fill material, improper foundation preparation, improper fill compaction, incorrectly designed fill slope, improper culvert design and installation within the fill can be major factors in mass failures. Bilby *et al.* (1989) cited mass failure of the fill batter as one of the most common causes of sedimentation in steeply sloping areas with unstable soils. Such landslides are common erosion mechanisms in areas where sediment production is mostly directed to streams (Mills, 1997). Sessions *et al.* (1987) suggested that improved road siting and building would reduce the frequency of landslides dramatically. The highest rate of runoff and sediment delivery to streams from outslopes occurs mostly in high hillslope areas where the fill batter is very long, very wide and very high.

Road Surface

The process influencing erosion in both insloping and outsloping sections of road surfaces is the same, but the direction of water flow is different. In outsloping erosion processes, the runoff is not delivered to the ditch, but flows directly to the fill slope or via drainage structures in the outsloping sections. An erosion problem occurs where the runoff concentrates at a specific point with high volume and velocity. At this point, both road shoulder and fill can be detached, eroded and transported to the forest ground or streams. There will be few erosion problems when the water flows slowly from the surface of road onto the shoulder and then onto the fill, and finally flows out of the road prism. In this case, any energy related to the action of runoff will be insufficient to detach soil or transport sediment downwards.

The process of outsloping the road surface by grading is one of the most common activities of forest road maintenance, and is done in order to control runoff and surface erosion. In this way, the runoff will flow slowly from the road surface onto the fill batter, through the shoulder of the road. This is the best way to reduce the velocity of runoff into ditches from the surface of the road, especially in flat areas. Increasing the number of outsloping and cross drains is a simple technique to disconnect sediment from roads to streams and thus reduce sediment delivery (USDA, 1999).

Fill Batter/Fillslope Erosion

Erosion from outsloped sections of roads is mostly related to the condition and stability of the fillslope. Most erosion in this section of a road comes from the shoulder and the fill, where the soil is not compacted properly and lacks stability following road formation. Soil can therefore be easily detached and transported downward by the forces of runoff and gravity. The amount of fill erosion depends on several variables: slope, pressure forces (energy) of runoff, the rate of soil infiltration, soil erodibility, gravitational forces, fill stability and vegetation cover on the shoulder and fill. The rate of instability is highest during the years immediately after road construction. The rate is also high for roads built on steeper terrain where the volume of excavated soil is high with consequent greater width of filling.

These issues of soil erosion and sedimentation delivery to streams from fillslopes have not been adequately considered by the research reviewed here. There are some comprehensive studies related to these problems, but they are seldom focused on a specific problem area like gully formation. Most researchers and managers seem to assume that the problems of fill batters are temporary and that, shortly after road construction, the problems will be solved because of revegetation (Megahan, 1980). The amount of sediment produced by road construction is directly related to the percent of the area taken by roads, the amount of protection given to the seeded slopes, and whether the road is given a protective surface (King, 1984).

2.3.6 Erosion Processes of Road Drainage Structures

Unsealed forest road systems are generally supported by installing a drainage structures. The road drainage structures collect and carry away the water flowing from the surface of roads and divert it to table drains, mitre drains, relief culverts or the fillslope. The most important purposes of installing drainage structures on a road are:

1. Reducing the distance water flows (road contributing length) on the road surface and in the adjacent table drains;
2. Decreasing the concentration and velocity of water runoff in order to decrease the energy available for detaching and transferring the particles;
3. Drying the road surface to enable continuous access along the road;
4. Controlling and reducing harmful environmental and economic effects on the elements at risk (soil and water) and road reconstruction;
5. Providing safe crossings over streams, rivers and other watercourses and by installing culverts, to prevent water pollution and transportation problems.

Erosion Processes Associated with Mitre Drains

Mitre drains are the most common and effective drainage structures in forest road systems located in smooth terrain and flatter areas. Mitre drain condition and characteristics like the channel roughness coefficient are sometimes more important than runoff delivery to the mitre channel because of their role in sedimentation. For example, the channel must be built with suitable dimensions, which can discharge the delivered runoff safely away from the road prism. Runoff overflows from the channel leading to the road surface destroy the channel sides, head and crowns. This usually occurs where the channel size is smaller than is necessary to carry the water delivered from the road prism.

There is a strong linear relationship between the required size of the channel and the volume of runoff delivery to the mitre drain. Therefore, the prediction of the volume of the runoff delivery to the mitre drain from the road prism is important in planning and installing a mitre drain with proper dimensions. When designing and installing drainage structures, the total runoff delivery to the inlet of a mitre drain system is less important than the rate of peak flow of runoff delivery. This is also true for other drainage structures like culverts.

Erosion Processes Associated with Culverts

A culvert is a pipe (made of plastic, steel or concrete) installed across a road to receive water discharged from the road prism. As discussed in Chapter 4, culverts are commonly associated with potential erosion and damage to water quality. The most important erosion processes associated with culverts are outlet erosion, and the relationship between the outlet and the nearest watercourse. Erosion at the inlet occurs when the structure of the head is insufficient to carry the water delivered from table drain. Water flow then overtops the road fill or flows onto the road surface and causes the culvert to fail (see also Chapter 4).

2.3.7 Road Construction

The occurrence of high levels of erosion and sediment delivery to streams in the few years following road construction is well documented by research. For example, Ketcheson and Megahan (1996) found that most surface erosion on forest roads occurs in the first year or within a few years after construction. About 84 percent of all sediment production resulting from surface erosion on forest logging roads was found to be produced during the first year after road construction in a central Idaho forest (Megahan and Kidd, 1972).

Other studies that also describe the effect of erosion following road construction include those of Fredriksen (1970), Garvin *et al.* (1979), Cline *et al.* (1981), Peters and Litwin (1983), Burroughs *et al.* (1984), Ward (1985), Burroughs and King (1989), Rice and Lewis (1991), Best *et al.* (1995), Grace *et al.* (1997), Tysdal *et al.* (1999), Fransen *et al.* (2001), Madej (2001) and Bagley (2002). These papers contain discussion of the effects of the time since construction, the effect of drain spacing, sub-soil, mass movement from batter slopes, slope angle of batter slopes and the effect of ground vegetation on erosion from the road prism and associated batter slopes.

2.3.8 Road Maintenance

Regular maintenance of roads is necessary for efficient and safe use of roads and to prevent adverse impacts on the environment. Road maintenance also plays an important role in the reduction of erosion and sedimentation (Yoho, 1980; Douglas *et al.*, 1983; Burroughs *et al.*, 1984; Orme, 1990; USDA, 2003). For example, Burroughs *et al.* (1984) stated that a simple grading at the end of the harvesting season can yield substantial benefits, since rutted roads produce twice as much sediment as levelled roads.

Regular maintenance schedules should include inspection of road structures, drainage facilities and the condition of the road surface. Road maintenance and traffic intensity have the highest impact on sediment production (Reid, 1981). Consequently, forest road maintenance should be focused on ensuring continued access, maintaining fully functional drainage structures, and minimising the adverse impacts on water quality (Reid, 1981; Burroughs *et al.*, 1984; USDA, 2003).

Generally, planning and implementation of a road maintenance program is a complex task because of the specialised technical knowledge, the cost and the management required for implementing regular maintenance (Patric and Kidd, 1982; Swift, 1986; Dissmeyer and Frandsen, 1988; USDA, 2003).

2.3.9 Soil Erosion and Water Quality Models

There are now many erosion, sediment, transport, runoff and water quality models which can be used to quantify different erosion processes. For example, the Universal Soil Loss Equation (USLE) is one of the oldest models and is used worldwide. It was first introduced by Wischmeier and Smith (1978) and then improved by Renard *et al.* (1991, 1997). This revised model has been known as RUSLE since 1997. The model comprises a linear combination of factors: rainfall erosivity and runoff (R), soil erodibility (K), slope length (L), slope steepness (S), land cover management (C), and support practices (P).

Moore *et al.* (1988) argue that the traditional USLE-based approaches to erosion are not suitable for characterizing ephemeral gully erosion processes. The USLE and RUSLE (Revised Universal Soil Loss Equation) are used mostly for estimating possible soil loss and sheet erosion in agricultural land; however, these models are also now used for other land such as forests after generalizing the factors and data required. Some new models have used a combination of factors which were first used in the USLE. A simple erosion rate and the annual soil loss from specific area can now be predicted and estimated using the USLE/RUSLE model.

Alternative models have also been developed. The WEPP (Water Erosion Prediction Project) model is a process-based model that can be used to estimate soil erosion and sediment yield (Flanagan and Livingston, 1995). The input factors of this model are soil type, climate, topographic conditions, and vegetation canopy or land cover. The WEPP model is difficult to apply because it requires a huge quantity of input data, and this data is sometimes difficult to collect. This model has been adapted for estimating erosion and sediment yield from forest roads, and has been used by the US Department of Agriculture, Forest Service for calculating sediment yield from forest roads for nearly 130, 000 different road segments, table drain (X-DRAIN), and cut and fill batter templates (Elliot *et al.*, 1999).

Sediment Model (SEDMODL) is a GIS-based road erosion and delivery model designed to identify road segments with high potential for delivering sediment to adjacent streams (NCASI, 1999, 2002). The recently developed Sediment Model (SEDMODL2) uses an elevation grid combined with other layers such as road, stream, soil, geology and rainfall layers to produce what is essentially a computer-generated version of the Washington Department of Natural Resources Standard Method for Conducting Watershed Analysis, surface erosion module (WDNR, 1997), and the Water Erosion Prediction Project (WEPP) soil erosion model. The model estimates background sediment, generation of sediment for individual road segments, road/stream intersections, and estimates delivery of road sediment to streams at the road-stream crossing point through road surface (NCASI, 2002).

While the WEPP and SEDMODL models could, in principle, be adapted in Australian conditions, the constituent parameters – for geology, soil and other characteristics - have been set for the North American conditions in which they were developed. Preliminary investigation revealed that these parameters are quite different from those applying in the case study area, and that adaptation of the models would require considerable work.

Some of the commonly used and more important erosion and water quality models are summarised in Table 2.9. The models can be classified into three main categories: conceptual, empirical and physical, depending on the simulation, algorithms and data needed (Merritt *et al.*, 2003).

Table 2.9. Commonly used soil erosion, sediment and water quality models

Model Name	Type of Model	Area of Interest	Reference
USLE (Universal Soil Loss Equation)	Empirical	Soil Erosion	Wischmeier & Smith, 1978
GUEST (Griffith University Erosion System Template)	Physical	Soil Erosion	Yu *et al.*, 1997
WEPP (Water Erosion Prediction Project)	Physical	Soil Erosion	Laflen *et al.*, 1991; Flanagan & Livingston, 1995
TOPOG (Topographic Catchment Modelling)	Physical	Soil Erosion	O'Loughlin, 1986; CSIRO, 2002
CREAMS (Chemical Runoff and Erosion from Agricultural Management Systems)	Physical	Water Quality	Knisel, 1980
SEDNET (European Sediment Research Network)	Empirical	Soil Erosion	Prosser *et al.*, 2001
EMSS (Environmental Management Support System)	Conceptual	Water Quality	Vertessey *et al.*, 2001
LASCAM (Large-scale Catchment Model)	Conceptual	Water Quality	Viney & Sivalapan, 1999 (University of Western Australia)
IHACRES (Identification of unit Hydrographs and Component flows from Rainfalls, Evaporation and Streamflow data)	Empirical/ Conceptual	Water Quality (Rainfall-Runoff)	Jakeman *et al.*, 1990; Jakeman & Hornberger, 1993
SEDMODL1 and SEDMODL2	Physical	Soil Erosion & Sediment Delivery (Water Quality)	National Council for Air and Stream Improvement, Inc. (NCASI), 1999, 2002

A conceptual model can be a simplified representation of the catchment area with a high-level description of catchment processes. Conceptual models "usually incorporate the underlying transfer mechanisms of sediment and runoff generation in their structure, representing flow paths in the catchment as a series of storage, each requiring some characterisation of its dynamic behaviour" (Merritt *et al.*, 2003:768).

An empirical model is one based primarily on the analysis of observations to characterize response from these data (Wheater *et al.*, 1993). Empirical models are generally the simplest of all three model types and the computational and data requirements for such models are usually less than for conceptual and physics-based models (Merritt *et al.*, 2003). Many empirical models are based on the analysis of catchment data, and parameter values are more often transferred from calibration at experimental sites (Merritt *et al.*, 2003). As these models can be implemented in situations with limited data and parameter inputs, they are particularly useful as a first step in identifying sources of sediment and nutrient generation (Merritt *et al.*, 2003). However, they are often criticised for employing unrealistic assumptions about the physics of the catchment system and its characteristics (Wheater *et al.*, 1993).

A physical model is a material, pictorial, and analogical representation of an actual system (Morton and Suarez, 2001). Reproducing a process or system in this way can simulate changes, confirm conceptual understanding, or review results of a computer simulation. Merritt *et al.* (2003) stated that physics-based models are based on the solution of fundamental physical equations describing stream flow and sediment and associated nutrient generation in a catchment. In theory, the parameters used in physical models are measurable and are 'known' (Merritt *et al.*, 2003). In practice, the large number of parameters involved and the heterogeneity of important characteristics means that these parameters must often be calibrated against observed data (Wheater *et al.*, 1993; Beck *et al.*, 1995).

2.3.10 Soil Erodibility

Soil erodibility is the resistance of soil to erosion processes, and is known as the K factor in most common soil erosion models, such as USLE. Erodibility is a quantitative value, experimentally determined in the USLE (Rosewell, 1993). The rate of soil erodibility varies according to soil shear strength and structure, texture, infiltration capacity, aggregate stability and soil properties, especially organic material and chemical contents. Soil erodibility is also defined as a measure of how easily the soil is eroded by running water. According to Laffan *et al.* (1996:17), "soil erodibility may be defined as the inherent susceptibility of a soil to the detachment and transportation of soil particles or aggregates by erosive agents such as rainfall, runoff, throughflow, wind or frost". Soil erodibility value is one of the major factors and/or measurements used to predict the volume of soil erosion and sediment, especially from forest roads where soil is bared during construction. Laffan *et al.* (1996) also stated that soil texture, structure, colour, aggregate stability, organic matter and the stoniness of the soil layer are the main factors used to assess soil erodibility in the field. The severity of soil erosion occurring in forest road systems depends heavily on soil erodibility, technical issues of road construction and maintenance. Soil erodibility is one the most important factors in predicting erosion from some road segments, especially from cut and fill batters and ditches. The soil erodibility factor (K) can be used for the following purposes:

- Forest operations, management, particularly in managing the snig track network;
- Soil loss estimation from sheet erosion (for example, using RUSLE);
- Estimating the maximum spacing between the road drainage structures (Table 2.10);
- Assessing, managing and controlling erosion hazards.

Table 2.10. Maximum spacing between drainage structures (mitre drains, culverts, cross banks) based on the soil erodibility and road grade

Road Grade (%)	**Soil Erodibility Class & Maximum Drain Spacing**		
	Low to Moderate	High	Very High
1-5	150 Metres	120 Metres	70 Metres
6-10	120 Metres	90 Metres	40 Metres
11-15	95 Metres	70 Metres	30 Metres
16-20	50 Metres	35 Metres	30 Metres

Source: Adapted from Forestry Commission of Tasmania (1993)

Table 2.10 shows the relationship between the soil erodibility class and maximum drain spacing in Tasmanian forests. The space between drains decreases as road grade and soil erodibility hazard class increases.

Suggested soil erodibility values (K factor) based on soil texture have been estimated for the state of NSW, Australia (Table 2.11). These values refer to the mid points of a texture class (Rosewell, 1993); it has therefore been suggested that it is better to use an average value for soils which lie between classes (Rosewell, 1993).

One of the main purposes of using this classification is to allocate variables to the categories as simply as possible for practical use. According to the results of research carried out in the last few decades (for example, Dissmeyer and Foster, 1980; Brown and Laffan, 1993; Forestry Commission of Tasmania, 1993; Rosewell, 1993), soil erodibility can be classified based on local geology classes, soil type, gravel content, vegetation or land cover classes, and also local experience, in order to assess the soil erosion hazard.

Table 2.11. Suggested values of the soil erodibility factor (K) for different soil textures in the state of New South Wales, Australia

Soil Texture	Symbol	Suggested K factor
Sand	S	0.015
Clayey sand	CLS	0.025
Loamy sand	LS	0.020
Sandy loam	SL	0.030
Fine sandy loam	FSL	0.035
Sandy clay loam	SCL	0.025
Loam	L	0.040
Loam, fine sandy	Lfsy	0.050
Silt loam	SiL	0.055
Clay loam	CL	0.030
Silty clay loam	SiCL	0.040
Fine sandy clay loam	FSCL	0.025
Sandy clay	SC	0.017
Silty clay	SiC	0.025
Light clay	LC	0.025
Light medium clay	LMC	0.018
Medium clay	MC	0.015
Heavy clay	HC	0.012

Source: Rosewell (1993:19)

Deep coarse sandy and coarse sandy soil are categorised as being in a very high erodibility class (Table 2.12). Although it is not easy to systematically separate the soil erodibility classes according to a specific soil type using this table, the location of soil in a forest (for example, wet or dry forest) is a key factor for classification of erodibility based on soil type. For example, in Australia, clayey, red clayey and stony loamy soils under wet or mixed forest are classified as belonging in the low erodibility class, whereas these soils have moderate erodibility when they are located under dry forest.

Table 2.12. Soil erodibility classes related to soil type

Level	Class	Soil type
1	Low	Clayey soil under wet and mixed forest, red clayey, very stony loamy soils under wet forest
2	Moderate	Loamy over clayey soils under wet forest, loamy soils, clayey and red clayey soil under dry forest, clayey, loamy and fine sand soils under Blackwood swamp forest
3	Upper Moderate to high	Organic soils, shallow loamy, loamy over clayey, sandy, coarse sandy, fine sandy, mottle clayey soils
4	High	Sandy over clayey, loamy, fine sandy over clayey soils under dry forest, sandy or silty soil under wet forest, sandy over clayey under dry forest, sandy soils under dry forest
5	Very high	Deep coarse sandy over clayey, coarse sandy soils under dry forest

Source: Brown and Laffan (1993); Laffan (1993)

2.4 Terrain Attributes

2.4.1 Overview

Topographic or terrain attributes data are very useful features of GIS systems and can be used to describe the morphology of the landscape, and to understand the influence of topography on the environmental processes leading to natural resource deterioration (Beven and Moore, 1993; Pallaris, 2000). Surface and hydrological information and terrain attributes can be automatically extracted from a Digital Elevation Model (DEM) using Digital Terrain Model (DTM). Surface terrain attributes such as slope, aspect, surface curvatures, flow direction and accumulation, Compound Topographic Index (CTI), and Stream Power Index (SPI) are generally derived or created by surface and hydrological analysis of DEM. These terrain attributes describe and identify the land (earth) surface situation, such as downslope flow movement and its direction, potential energy of water flow, zones of enhanced erosion and deposition, the possible rate of runoff and overland flow, and the erosive power of overland flow.

2.4.2 The Role of Terrain Models in Predicting Soil Erosion and Water Quality Impacts

Digital Elevation Models (DEMs) are primary models that can be used in the analysis of catchment topography; they consist of an array of numbers representing the spatial distribution of elevations above some arbitrary datum in a landscape (Moore *et al.*, 1993). In addition, the spatial distribution of terrain attributes is generally represented by DEMs: "A DEM is a 3-dimensional representation of the Earth's surface" and is used for applications requiring 3-D topographic information (RADARSAT, 2000:1). The terrain attributes, or structuring a network of elevation data for its acquisition and analysis, can be represented using the three basic formats of a DEM: by square-grid, triangular irregular (TIN) and contour-based networks (Moore *et al.*, 1993).

Hutchinson and Gallant (2000) classified topographic sources into three main classes: surface-specific point elevation data, contour and streamline data, and remotely sensed elevation data. The surface-specific point elevation data can include high and low points, crest and saddle points, and points on streams and ridges which can be obtained by ground survey and manually assisted photogrammetric stereo models (Markarovic, 1984; Clarke, 1990). Such data can commonly be obtained for detailed surveys of relatively small experimental catchments, but they are less often used for larger areas because the process is long and expensive (Hutchinson and Gallant, 2000). On the other hand, contour data are still the most common terrain data source for larger areas. These data can be digitised from existing maps or can be generated automatically from photogrammetric stereo models (Lemmens, 1988; Hutchinson and Gallant, 2000). Finally, remotely sensed elevation data can be very useful and can also provide broad spatial coverage. Although remote sensing data have a number of generic limitations with significant random errors, there are many ways to reduce these limitations like "averaging of data obtained from multiple passes of the sensor [which] can reduce these errors, but at greater costs" (Hutchinson and Gallant, 2000:34).

Topographical analysis can be used to estimate the primary topographical attributes throughout the catchment. For example, Moore and Burch (1986b) and Moore *et al.* (1988) used a Topographical Analysis Program for the Environmental Sciences (TAPES) to estimate the following primary topographical attributes throughout a catchment:

1. Unit area or upslope contributing area (A_b) per unit length of contour (units = m^2/m), where $A_b = A/b$ and A is the upslope contributing area and b is the length of its contour segment;
2. Slope (S, see formula 2.3);
3. Profile curvature (C or K_p, units = m/m^2) as shown in formula 2.9;
4. Aspects that will illustrate by E or Ψ icon (units = degrees clockwise from north) (see also formula 2.6). This is defined as the down-slope direction orthogonal to the contour.

TAPES is a useful tool describing the morphology or shape of the landscape by dividing a three-dimensional terrain into small irregularly shaped elements or polygons based on contour lines, that are assumed to be equipotential lines, and their orthogonal, streamlines

(Moore and Burch, 1986b; Moore *et al.*, 1988). TAPES has recently been developed and documented as a GIS based tool for ArcGIS9 by Gallant and Wilson (2004).

Moore *et al.* (1988) investigated the effects of topography on the distribution of surface soil water and the location of ephemeral gullies by using terrain and topographic analysis methods. They found that when the photographs of the catchment were digitally improved "to highlight differences in soil water content, zones of higher water content could clearly be seen pointing out from the wet areas along the remnant furrow lines" (Moore *et al.*, 1988:1103). This study shows that soil water content across the catchment was connected with many topographic attributes, and the values of these attributes could be deduced using a contour-based topographic analysis. Slope and aspect are of greatest importance as primary attributes to predict flow distributions and the soil water context.

2.4.3 Primary Terrain Attributes

Elevation

Elevation information is generally represented in the form of a Digital Elevation Model (DEM) or Digital Terrain Model (DTM). A DEM is a cell-based raster representation of the continuous surface of the earth delineating or showing elevation above a given datum that is a known height in metres above sea level (Pallaris, 2000). DTM is a set of techniques used to derive or present a DEM (Hengl *et al.*, 2003). DTM is generally used for derivation of terrain parameters (Moore and Wilson, 1992; Hengl *et al.*, 2003). Elevation is base terrain information for spatial analysis and extracting derivative data sets and terrain attributes.

Slope

Slope is one of the most important foundation primary attributes; it is derived directly from a DEM. Slope can be defined as the rate of change of elevation in the direction of steepest descent. "It (Slope) affects the velocity of both surface and subsurface flow and hence soil water content, erosion potential, soil formation, and many of other important processes" (Gallant and Wilson, 2000:53). Slope can be calculated in two ways: as an angle from the horizontal in degrees (tan β) and as a percentage (100* (Rise/ Run) (Burrough, 1986; Burrough and McDonnell, 2000; Gallant and Wilson, 2000):

$$S = \tan \beta = b/a \tag{2.3}$$

Slope can also be calculated by the Finite Differences (FD) method:

$$S_{FD} = \sqrt{p} \tag{2.4}$$

where FD is finite differences and $p = X^2 + Y^2$ (X = Run and Y = Rise). Gallant and Wilson (2000) and Jones (1996) believe that this method is slightly more accurate than other methods for calculating slope, such as the D8 method. The Finite Differences formula is based on the elevation in the four cardinal directions (north, south, east, and west). In the D8 method, slope is computed using the steepest downhill slope to one of the eight nearest neighbours cells (Gallant and Wilson, 2000). The D8 method generally gives smaller average slopes than the finite differences method when the down-slope direction is the only target from eight possible directions (Moore *et al.*, 1993d; Jones, 1996; Tarboton, 1997):

$$S_{D8} = \max_{i=1,8} \frac{z_9 - z_i}{h\phi(i)} \tag{2.5}$$

where $\phi(i) = 1$ for cardinal neighbours (I=2,4,6, and 8) and $\phi(i) = \sqrt{2}$ for diagonal neighbours, h is the grid spacing of DEM, and z is the flow direction numbering convention.

Aspect

Aspect (Ψ) has been defined as the orientation of the line of steepest descent, and will usually be measured in degrees clockwise from north (Gallant and Wilson, 2000). Aspect and slope are useful for visualizing landscapes and estimating the solar radiation. An area with a very small slope may be considered to have undefined aspect (Gallant and Wilson, 2000 cited from Mitasova and Hofierka, 1993). Aspect is also significant for estimating solar insolation, evapotranspiration, distribution and abundance of fauna and flora, and ecological assessment and surveys. In addition, the downslope direction will be calculated by deriving the aspect as the maximum rate of change in value from each cell to its neighbours (Pallaris, 2000). Downslope direction indicates the direction of water flow over the terrain being analysed:

$$\psi_{FD} = 180 - \arctan\left(\frac{z_y}{z_x}\right) + 90\left(\frac{z_x}{z_x}\right) \text{ Or } \psi_{FD} = 180 - \arctan\left(\frac{B}{A}\right) + 90\left(\frac{A}{|A|}\right) \qquad (2.6)$$

where Ψ is aspect and z (A and B) is flow direction numbering convention.

Flow Direction

The flow direction is another terrain attribute that is derived from DEMs. The flow direction is generally used to define the water flow from one cell into the target cell (USGS-NASA, 2001). "The primary flow direction, FLOWD, is an approximate surrogate for aspect" (Gallant and Wilson, 2000:55).

$$\text{FLOWD} = 2^{j-1} \qquad (2.7)$$

where $j = \arg\max_{i=1,8} \frac{z_9 - z_i}{h\phi(i)}$. The value of i that gives the largest slope value is the direction of steepest descent. Flow direction is essentially an aspect orientation map; the function is based on a D8 algorithm introduced by Moore *et al.* (1991) which computes 8 possible directions related to the eight cells into a target flow travel cell (Pallaris, 2000). Flow direction directly derives from a depressionless or filled (sink) DEM. Flow direction is one of the most important primary terrain attributes in the watershed delineation process and also when applying Digital Terrain Analysis to a hydrological study using GIS. This will be further discussed in Chapters 6 and 7.

Flow Accumulation

Flow accumulation is calculated directly from a computed flow direction. It is also the count for each cell of how many upstream cells would contribute to it in terms of their flow direction (Pallaris, 2000). Flow direction and accumulation are used for calculating flow, accumulation area, catchment runoff, and stream network in watershed delineation applications. The amount of discharge water is generally proportional to the accumulation area. According to Moore *et al.* (1991) and Pallaris (1999), the accumulation area can be used to calculate the volume of water which is potentially available to each cell from an upslope area. The volume of water or runoff will be higher downhill and in the valley bottom because of the bigger contribution area and higher volume of water collection. The most important benefits of this process are identifying the overland flow contribution area within a catchment. Pallaris (1999) showed that the conception of the accumulation area of a given cell is the sum of all the upstream cells that drain it (Figure 2.4).

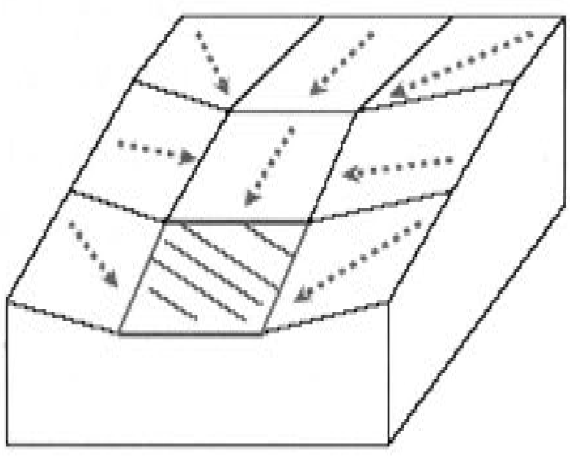


Figure 2.4. Accumulation area of the shaded cell, catchment runoff pattern
Source: Pallaris (2000)

Plan Curvature

It is commonly observed that water converges as it flows across land; small streams meet to form larger streams which in turn coalesce to form rivers. This natural tendency can be predicted and mapped using a technique based on DEM, called 'Plan Curvature'. Plan curvature has been defined as a measure of topographic convergence and divergence, and is a measure of the propensity of water to converge as it flows across the land (Gallant and Wilson, 2000). Plan curvature (K_c) describes the curvature of the surface perpendicular to the slope direction. K_c also shows the rate of change of aspect along a contour (Moore *et al.*, 1993; Enander, 1998). It is also known as contour curvature. The value of K_c also defines the rate of change of aspect along a contour. The value of plan curvature is negative for deriving flow on ridges and it is positive for converging flow in valleys (Gallant and Wilson, 2000). Surface curvature identifies zones of enhanced erosion and deposition that are represented by two important attributes; plan and profile curvatures (Pallaris, 2000). The plan curvature is defined as:

$$K_e = \frac{z_{xx}z_x^{2} - 2z_{xy}z_x z_y + z_{yy}z_y^{2}}{p^{3/2}} \tag{2.8}$$

where K_e is plan curvature, z is flow direction numbering convention and p is as defined in equation 2.4.

Profile Curvature

The rate of change of potential gradient, which is very important for characterising changes in flow velocity and sediment transport and delivery to stream, can be measured from profile curvature (Gallant and Wilson, 2000). In addition, K_p shows the rate of change of slope down a flow line. As Gallant and Wilson (2000) and Pallaris (2000) argued, the plan curvature is defined as the curvature in the horizontal plane of the contour line, but the curvature in the vertical plane of a flow line is known as profile curvature (K_p):

$$K_p = \frac{z_{xx}z_x^{2} + 2z_{xy}z_x z_y + z_{yy}z_y^{2}}{pq^{3/2}} \tag{2.9}$$

where K_p is profile curvature, z and p are as defined in equation 2.5 and q is discharge per unit width.

Tangential Curvature

Tangential curvature (K_t) is the plan curvature multiplied by the sine of the slope angle (Moore *et al.*, 1993; Wilson and Gallant, 2000). Tangential curvature is also defined as a curvature in an inclined plane perpendicular to both the direction of flow line and the surface (Wilson and Gallant, 2000). K_t can provide more accurately the measurement alternative paths of flow convergence and divergence than plan curvature because there are no extremely large values when the slope is small (Mitasova and Hofierka, 1993). K_t is estimated as:

$$K_t = \frac{z_{xx} z_x^2 - 2z_{xy} z_x z_y + z_{yy} z_y^2}{pq^{1/2}} \qquad (2.10)$$

where K_t is tangential curvature, and z, p and q are as defined earlier in equations 2.8 and 2.9.

2.4.4 Secondary Terrain Attributes

The secondary terrain attributes are generally computed or calculated from two or more primary attributes (Moore *et al.*, 1993; Wilson and Gallant, 2000). These attributes are very important for predicting water movement processes through the landscape. They play an important role when estimating the effects of topography on redistribution of water in the landscape and in modifying the amount or rate of solar radiation received at the surface (Wilson and Gallant, 2000). The most important secondary terrain attributes are Compound Topographic Index (CTI), Stream Power Index (SPI), Radiation Index (RI) and Temperature Index (TI). CTI and SPI are the two secondary terrain attributes most relevant to this study.

Compound Topographic Index (CTI)

CTI can be derived from primary attributes at different scales (Moore *et al.*, 1993; Mackey *et al.*, 1994). Generally, CTI (also called Topographic Wetness Index (TWI)) is used to predict soil moisture status, which is important to ecological relationships, road construction and logging (Mackey *et al.*, 1994). CTI measures the wetness of a site and is useful in identifying wetlands and other moist soil conditions. CTI is a function of the upstream contributing area and the slope of the landscape that combines the catchment area above a cell with the local slope (USGS-NASA, 2001). In addition, CTI answers the questions of potentially how much water flows to a specific site?, and how fast does water drain from a site? "The CTI is calculated using the flow accumulation (FA) layer along with the slope as: CTI= ln (FA/ tan (slope))" (USGS-NASA, 2001:4). CTI value in flat areas is obtained by assuming a slope value of 0.001 (USGS-NASA, 2001). The amount of upstream catchment area draining into each cell is generally determined from the flow accumulation data.

Moore *et al.* (1993) argued that identifying soil water content and surface saturation zone are the most important objectives for using CTI. They developed the compound topographic attributes, or CTI, equation as follows:

$$W_T = \ln\left(\frac{A_s}{T \tan\beta}\right) \text{ Or } W = \ln\left(\frac{A_s}{T \tan\beta}\right) \qquad (2.11)$$

In equation 2.11, T is transmissivity when the soil profile is saturated, and W_t and W are both often referred to as wetness indices (Moore *et al.*, 1993:17). Although there are some slightly different forms and definition, the spatial distribution and size of zones of saturation and/or variable source of areas for runoff generation are the main factors of CTI forms, definition and application (Moore *et al.*, 1993).

Stream Power Index (SPI)

Stream Power Index (SPI) generally measures the erosive power of flowing water with respect to the assumption of proportional discharge from a specific catchment area (Wilson and Gallant, 2000). Moore *et al.* (1991) stated that SPI has been used in many studies of erosion and sediment transport for measuring the erosive power of flowing water, that is, the energy of water movement down a slope. The SPI also predicts the net erosion rate in areas of profile convexity, tangential concavity, and net deposition in areas of profile concavity (Wilson and Gallant, 2000). The SPI is generally calculated by the equation:

$$\mathrm{SPI} = A_s \tan\beta \qquad (2.12)$$

where A_s is a specific catchment area and β is slope gradient. It is also computed as:

$$\Omega = \mathrm{pgq} \tan\beta \qquad (2.13)$$

where pg is the unit weight of water, q is the discharge per unit width, and β is the slope gradient in degrees (Wilson and Gallant, 2000).

Moore and Burch (1986a) and Moore and Wilson (1992, 1994) improved an equation for calculating the LS-Factor (slope length (L) and slope gradient (S) factors) in the Revised Universal Soil Loss Equation (RUSLE). This equation is based on stream power theory as a second compound index, using a variant in place of the LS-Factor that is limited for slope length more than 100 metres and slope gradient more than 14 degrees. The equation for the LS-Factor calculation is:

$$LS = (m+1)\left(\frac{A_s}{22.13}\right)^m (\sin\beta / 0.0896)^n \qquad (2.14)$$

where A_s is a specific catchment area, m is slope length exponent ranges from 0.4 to 0.6, $\sin\beta$ is sine of the slope and n is slope steepness exponent ranges from 1.2 to 1.3. The details of this calculation (LS-Factor) and related issues will be discussed in Chapter 5.

The primary and secondary terrain attributes for quantitative terrain analysis relevant to this study are those developed by Speight (1974), Moore *et al.* (1993) and Wilson and Gallant (2000). These are summarised in Tables 2.13 and 2.14.

Table 2.13. Primary terrain attributes for quantitative terrain analysis calculated by Speight (1974), Moore *et al.* (1993) and Wilson and Gallant (2000)

Attribute	Units	Definition	Formula
Aspect	Degrees (Clockwise from North/ 0-360)	Aspect is the slope direction. The aspect data show the direction of maximum rate of change in elevation between each cell and its eight neighbours.	$\psi_{FD} = 180 - \arctan\left(\frac{B}{A}\right) + 90\left(\frac{A}{\lvert A \rvert}\right)$
Elevation	Metres (from above sea level)	Elevation is the proportion of cells in a user-defined circle lower than the centre cell	-
Flow Accumulation	Number of cells	The amount of upstream catchment area draining into each cell.	-
Catchment Area	Litre or m^3	Catchment area is an area draining to catchment outlet. It is used to calculate the runoff volume.	-
Flow Direction	None or Nominal Code (1-128)	The direction of flow from one cell into the target cell (steepest down-slope neighbour).	-
Flow Path Length	Metres	Maximum distance of water flow to a point in the catchment.	-
Plan Curvature	100 m^{-1}	Plan curvature (K_e) describes the curvature of the surface perpendicular to the slope direction. K_e also shows the rate of change of aspect along a contour. Plan curvature is also known as contour curvature.	$K_e = \frac{z_{xx} z_x^2 - 2 z_{xy} z_x z_y + z_{yy} z_y^2}{p^{3/2}}$
Profile Curvature	100 m^{-1}	Profile curvature (K_p) shows the rate of change of slope for each cell in the direction of slope. It also shows whether the slope is convex or concave and determines the pathway of water depositional material. Profile curvature is also known as slope profile curvature.	$K_p = \frac{z_{xx} z_x^2 + 2 z_{xy} z_x z_y + z_{yy} z_y^2}{pq^{3/2}}$
Tangential Curvature	100 m^{-1}	Tangential curvature (K_t) is the plan curvature, which is multiplied by the sine of the slope angle.	$K_t = \frac{z_{xx} z_x^2 - 2 z_{xy} z_x z_y + z_{yy} z_y^2}{pq^{1/2}}$
Catchment Length	Metres	Distance from highest point of catchment to outlet. Catchment length is very important for studying overflow.	-
Slope	%	Slope measures the rate of change of elevation in the direction of steepest descent.	100* (Rise/ Run) or $S_{FD} = \sqrt{p}$ (FD=Finite Differences $p=z^2_x+z^2_y$)
Upslope Contributing Area (USCA)	m^2 or number of cells	Catchment area above a short length of contour. This is extremely significant for calculating runoff volume and steady-state runoff rate.	$A_s = A/L$

Table 2.14. Secondary terrain attributes for quantitative terrain analysis calculated by Speight (1974), Moore *et al.* (1993) and Wilson and Gallant (2000)

Attribute	Units	Definition	Formula
Compound Topographic Index (CTI)	Nominal Code	CTI is a function of the upstream contributing area and the slope of the landscape that combines the catchment area above a cell with the local slope (USGS-NASA, 2001). CTI is used to predict soil moisture status/ wetness index.	CTI= ln (FA/tan(slope)) FA: Flow Accumulation Or $W_T = \ln\left(\frac{A_s}{T \tan\beta}\right)$ A_s = The specific contributing area T=The soil transmissivity
Stream Power Index (SPI)	Nominal code	Measure of erosive power of flowing water based on assumption that discharge is proportional to specific catchment area.	SPI=FA* (S/100) or FA* tanβ Or SPI= A_s * tanβ
Radiation Indices	Cal/cm^2/dayLangley/day MJ/m^2/dayW/m^2	1. Estimates the total short-wave irradiance. 2. Estimates the incoming or atmospheric long wave irradiance. 3. Estimates the outgoing long wave irradiance. 4. Estimates the net radiation or surface energy budget at the earth's surface.	1. $R_t = (R_{th} - R_{dh})F + R_{dh}v + R_{th}(1-v)\alpha$ 2. $L_{in} = \varepsilon_a \sigma T_a^4 v + (1-v)L_{out}$ 3. $L_{out} = \varepsilon_s \sigma T_s^4$ 4. $R_n = (1-\alpha)R_t + \varepsilon_s L_{in} - L_{out}$

Computer techniques have been used for predicting runoff and soil erosion since the 1980s, when GIS became a common software tool for mapping and analysis (Mitasova *et al.*, 1996). Work in the 1990s (Hutchinson, 1989, 1997, 2000) to integrate ANUDEM software with the ArcGIS system greatly facilitated the use of terrain models for predicting the likelihood of the exact locations of soil erosion. Creating reliable maps of terrain attributes derived from DEMs is an ongoing process. Moore *et al.* (1988) argued that a high value of Compound Topographic Index (CTI) can be a useful factor in predicting the location of ephemeral gully erosion which occurs away from the main drainage ways (see also Table 2.15). Table 2.15 summarises the principal variables and factors used for predicting the risk to soil and water quality arising from forest road systems in this study.

Table 2.15. Factors used for predicting the risk of water quality impacts caused by forest road systems in this study

Factor	Equation	Derived from	Range of effects
CTI	$W_t = \ln(A_s / \tan\beta)$	DEM	Low-High
SPI	$SPI = A_s * \tan\beta$ or $SPI = A_s / (S/100)$	DEM	Low-High
Elevation	-	DEM	Low-High
Slope	$S = \tan\beta = b/a$	DEM	Low-High
Distance (Length) to stream	-	DEM/Measure/ Observation	Short-Long
Gully/Soil Erosion Index	$G_{index} = 0.2\ (A_s * \Psi * \tan\beta)^{0.25}$	Measure/Range	Low-High
Contribution area of drain	CA= CL* CW	Observation/ Measure	Gully-Diffuse
Upslope Contributing Area	$A_s = A/L$	Measure/ calculation	Low-High and Gully-Diffuse

2.5 Summary and Conclusions

Risk assessment is now an inseparable part of all types of management systems. The most important question asked by potential investors in a project is: how likely is the project to go wrong? How can this risk be assessed? Risk is normal, and even highly sophisticated tools cannot prevent all risks from occurring in a specific project. Risk assessment and related management processes can, however, reduce and minimise the risk to outcomes of a project. Risk assessment is a useful, even essential tool, in a forest management system, especially for managing forest roads, which are responsible for most soil erosion and water quality impacts. Road layout, technical problems in the building of roads and drainage structures, and the values of terrain attributes all play important roles in identifying and assessing the risks involved in forest road systems.

Risk assessment is now commonly applied to the management of projects or operations, especially where the consequences of failure are high. These include design of passenger aeroplanes and civil engineering works such as bridges. The process is one of identifying risks, estimating the probability that the risk will occur, and the costs involved in the worst case. A rational process of risk avoidance or reduction can then take place. For forest roads, the most important element of risk to the environment is that of increased erosion and additional sediment loading in watercourses.

Research studies on the effects of forest practices confirm that forest roads are the source of high rates of soil erosion and sediment delivery to streams. Where possible, forest roads, skid trails and landings should be built on stable soil and avoid steep terrain, landslide-prone areas, wetlands, and poorly drained areas in order to reduce sediment delivery to streams. Of particular concern is the high risk of soil erosion and water quality impacts resulting from existing older forest roads associated with a lack of proper design and ineffective maintenance. However, a newly built road on a steep slope is also likely to result in harmful impacts on water quality and other aspects of the environment.

To sum up, the problems of soil erosion and water quality impacts from forest roads are well covered by research. However, one of the most important questions for forest managers is still not completely answered, that is: how can forest managers, in practice, prevent or reduce the impacts of forest roads?

The key factors in the production of erosion of this nature are associated with the collection of water which ends up on the road's surface, and the slope of the road and the terrain; these all affect the road drainage structure and the ability of the soil and the road surface to resist erosion. These can be quantified using GIS techniques and DEM analysis. The most important factors that need to be calculated in this quantification are CTI, SPI, distance between road and stream, soil loss and curvatures. These will all be discussed in Chapters 5, 6 and 7.

Chapter 3
Description of Case Study Area

3.1 Introduction

For this study, it was fortunate that a plantation forest with an existing road network, developed over a long period, was located near the Australian National University. Stromlo Forest comprises about 10,000 ha, and – prior to a severe bushfire in January 2003 – it was stocked mainly with radiata pine. The blocks that comprised the Stromlo Forest management area were thoroughly inspected before finalising its selection as a study area in order to meet the objectives and test the possibilities of applying the methodology of the research in that area. Thus the type of forest, roads and drainage structures, topography and the distribution of the existing roads on slopes were all considered when selecting the study area. The possibility of soil erosion and water sedimentation problems occurring were also considered as an important criterion of the selection process.

The objectives of this chapter are to explain the selection of the study area and to describe its characteristics. In January 2003, a severe bushfire destroyed over 90% of the growing stock in the forest. The consequent effects on data collection will be discussed.

3.2 Location of Study Area

Stromlo Forest, ACT (Australian Capital Territory), is located on the western edge of Canberra, approximately 10 kilometres west of the city centre (Figure 3.1). The study site is a small area within the Murrumbidgee River Catchment, located in the southeast of that catchment (Figure 3.2). The Murrumbidgee River is one of Australia's main rivers and the second largest river in NSW; it flows through ACT from south to north (Baskin *et al.*, 1996). This river drains major areas of the Murray Darling Basin. The area drains into the Molonglo River, a branch of the Murrumbidgee River, which flows through Canberra. The study area coordinates are latitude -35.26° South (6,096,100 meters) and -35.37° South (6,083,900 meters) and longitude 148.92° East (674,660 meters) and 149.10° East (690,900 meters).

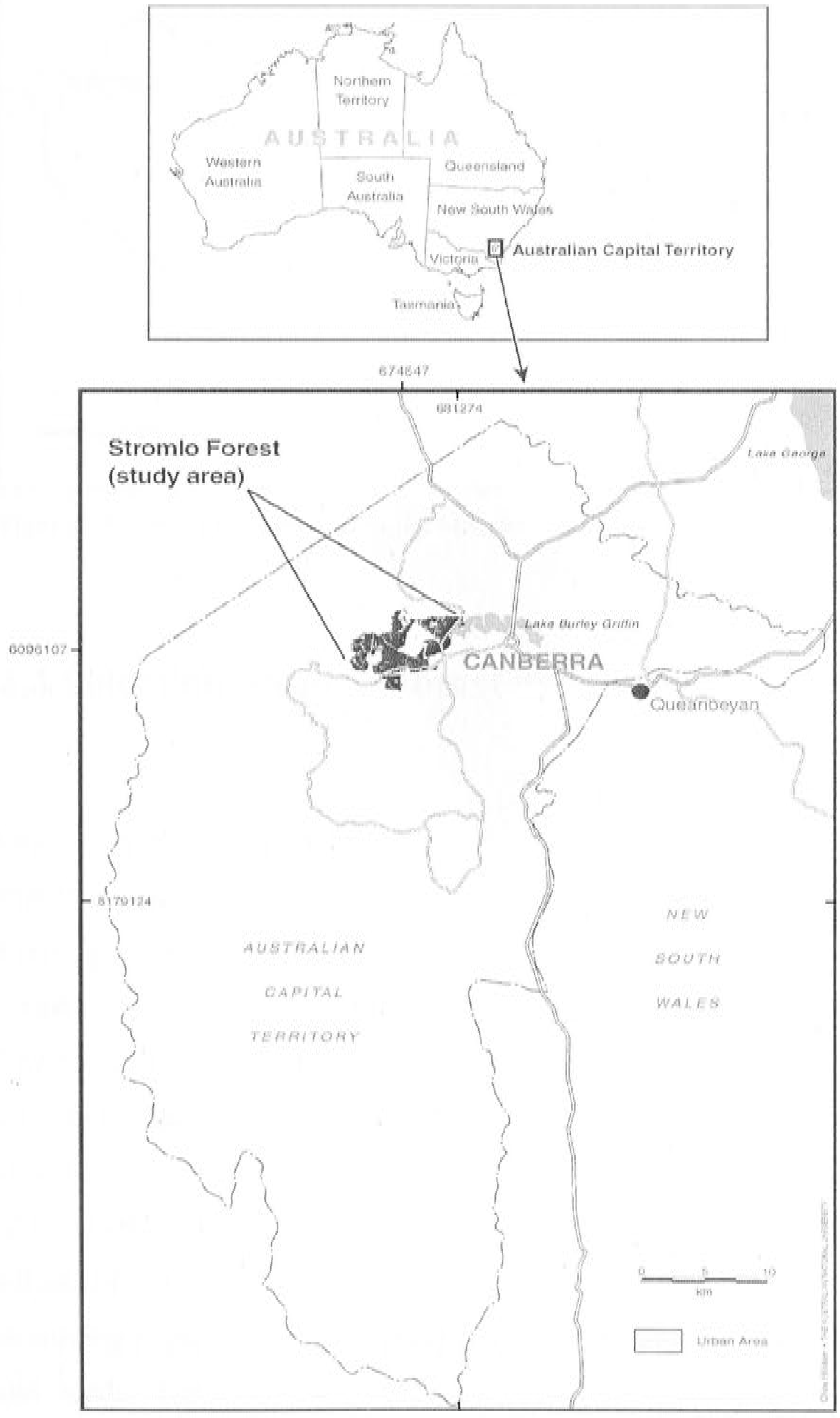


Figure 3.1. Location of the study area in the Australian Capital Territory

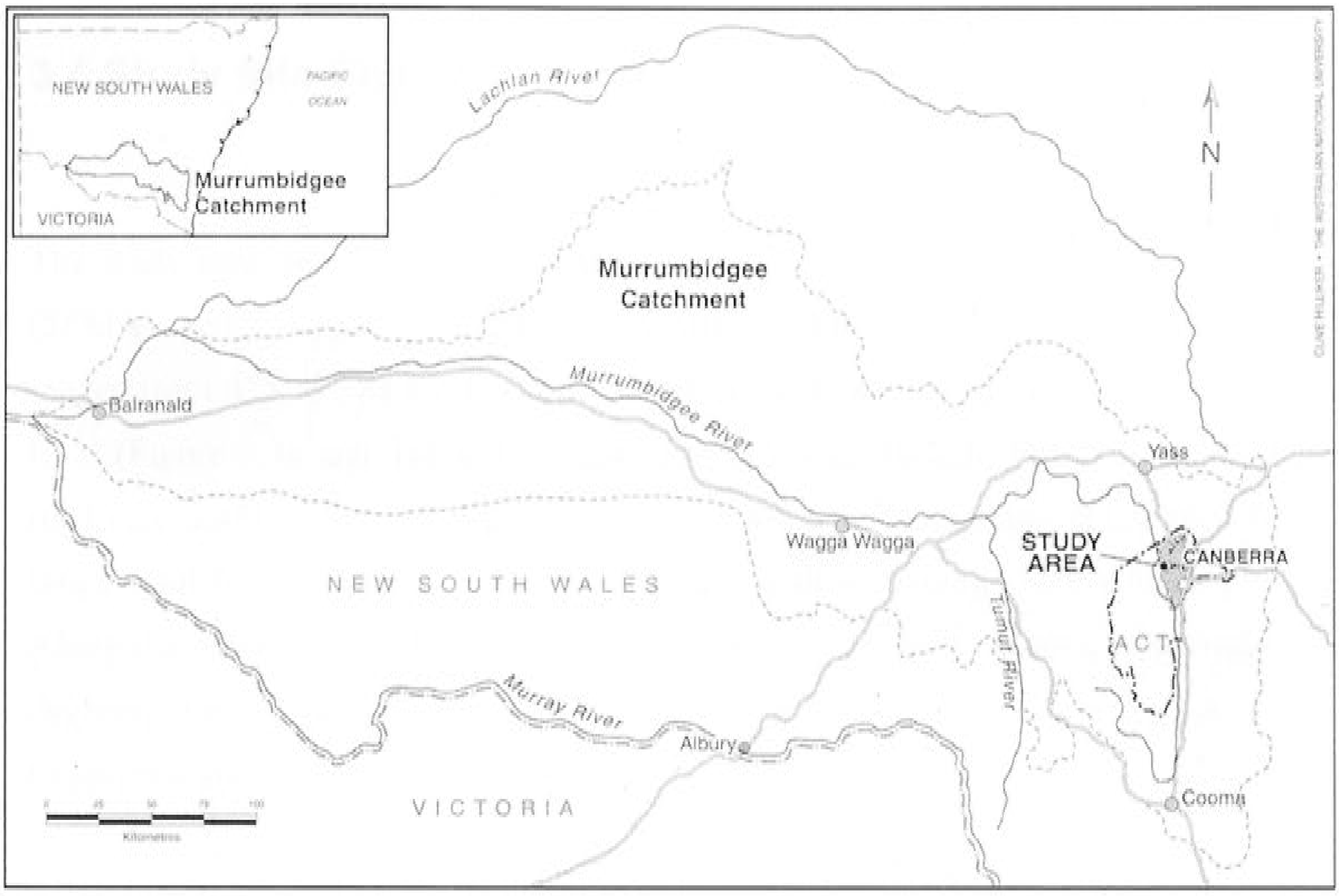


Figure 3.2. Case study area within the Murrumbidgee River Catchment area

3.3 Selecting Stromlo Forest as the Case Study Area

One of the main aims of this study was to devise a practical method for assessing the risk that the condition of existing forest roads would cause impacts on water quality. Stromlo Forest provided an appropriate and convenient case study area for this work. The existing forest roads and their design and physical characteristics, accessibility of the area, and the low costs of doing field work were important factors in the choice of Stromlo Forest as the case study area. Characteristics of the forest roads which were important for achieving the research aims are that most roads in the study area were built more 30 years ago and, although there was no technical information related to their condition, they demonstrate the effects of traffic, and of good and poor design and maintenance. These roads were not built according to present codes of practice and have many problems that are common to existing old roads. They also present many opportunities where risk assessment and targeted management could improve their impacts on soil erosion and water quality.

3.4 Study Site Characteristics

The study area was located in an area known as the Stromlo Forest Management Area (SFMA), comprising 2307 hectares of plantation forest. Elevation of the case study area ranges from 455 to 782 metres above sea level with an average of 590 metres above sea level (Figure 3.3a and Table 3.1). The topography of Stromlo Forest is characterized by relatively uniform low hills and the study area has an undulating landscape. The slopes range from 0 to 93 percent (0 to 43 degrees) with an average of 9 percent (5 degrees). Along the edge of Mount Stromlo itself, the slope steepness exceeds 92% (more than 40 degrees). Other characteristics of the study site are explained later in this thesis (see Chapters 6 and 7).

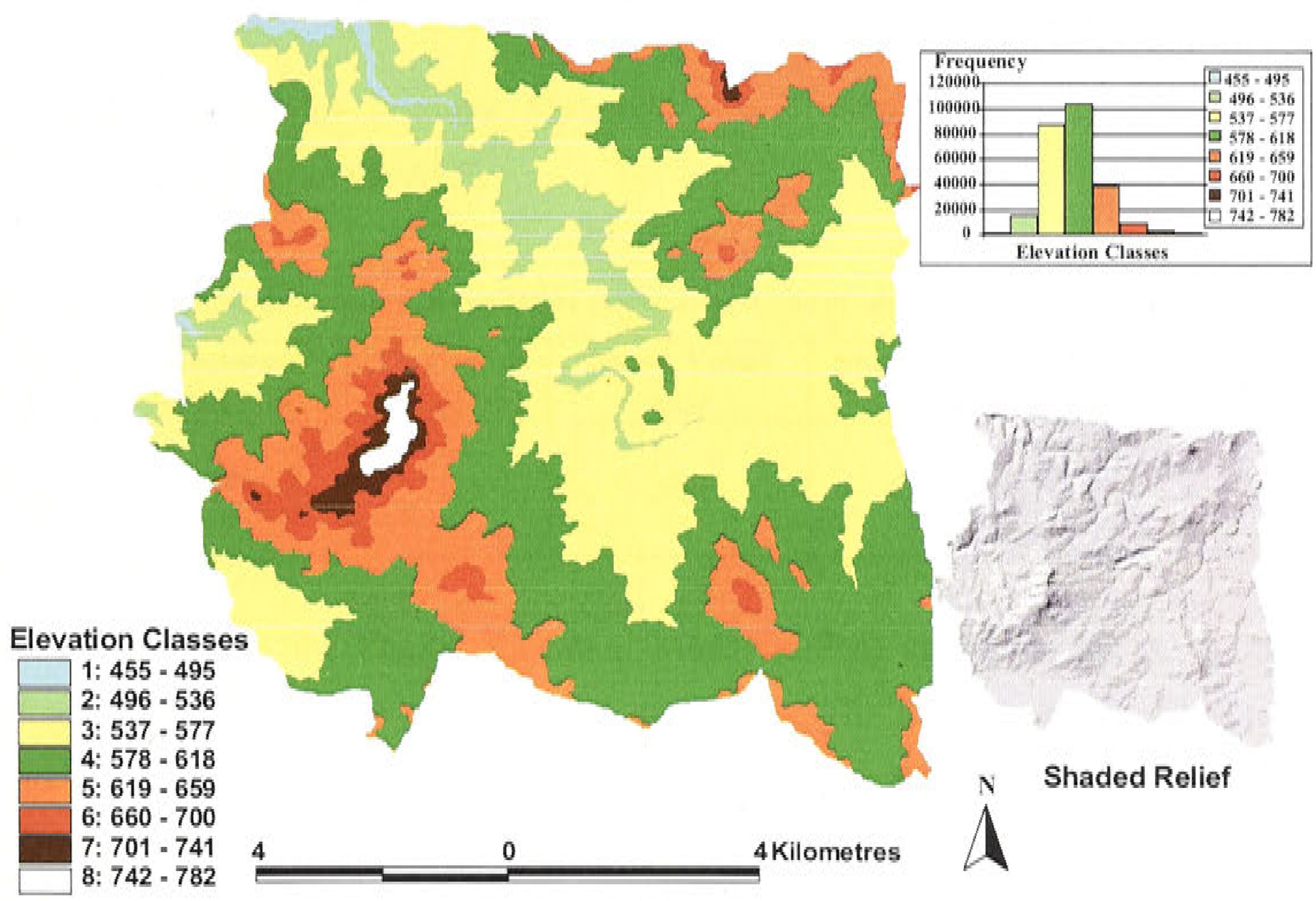


Figure 3.3a. Maps of DEM and shaded relief

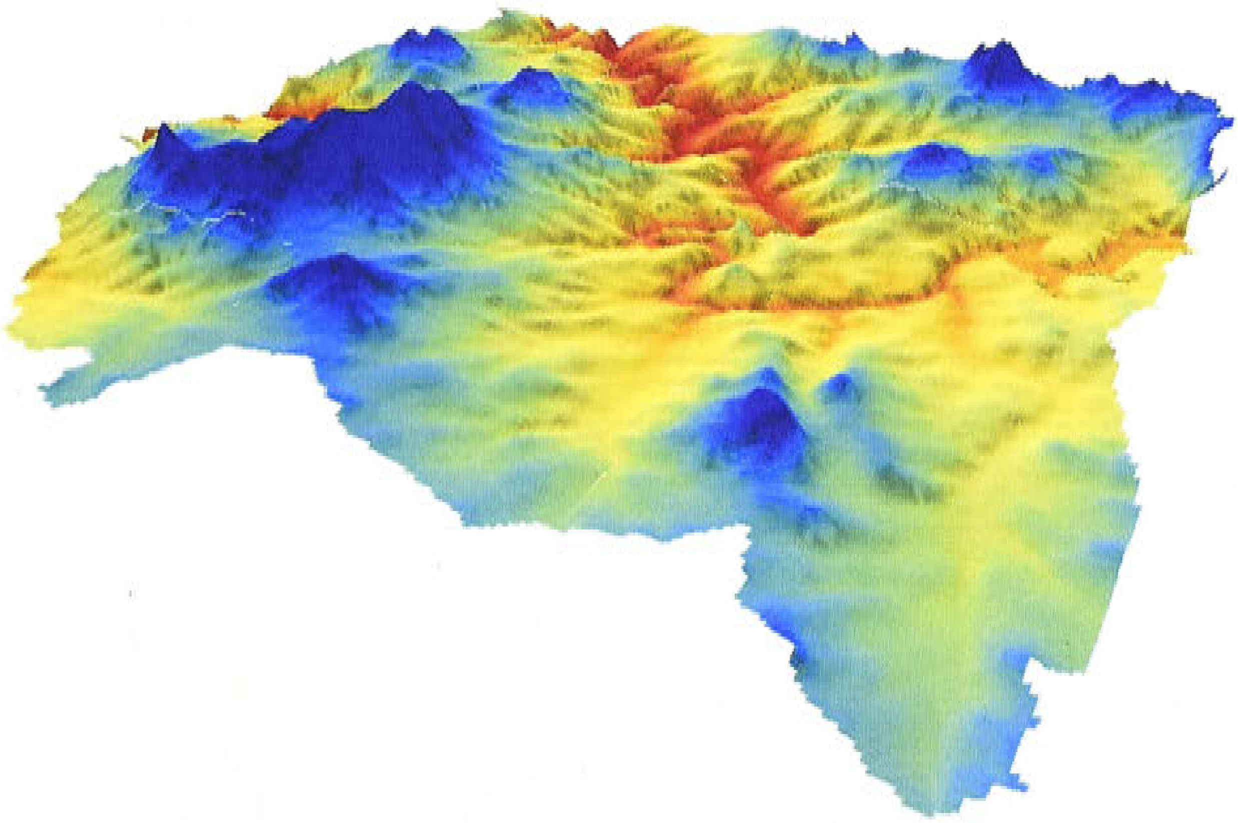


Figure 3.3b. Three-dimensional view of the study area (scale as for Figure 3.3a)

The study area drains into the Molonglo River, one of the main branches of the Murrumbidgee River in the ACT.

Table 3.1. Statistical description of the DEM (elevation) of the study area

Area (ha)	Minimum Value (m)	Maximum Value (m)	Mean Value (m)	Standard Deviation	Range (m)
10477	455	782	590	41	327

Figure 3.3a shows the Digital Elevation Model (DEM) and a shaded relief map, and histogram of the elevation classes of the study area. The DEM was first subjected to pit removal in order to create a depressionless elevation layer for creating a shaded relief map and other related maps. This process will be explained later, where DEM analysis and watershed delineation are described in Chapters 6 and 7. As can be seen in Figure 3.3a, most of the elevation of the study area falls within the range 490-700 meters above sea level. A three dimensional image of the study area, created from DEM using ArcGIS, is shown in Figure 33.b.

3.4.1 Vegetation

Before the fire of January 2003, Stromlo Forest was mostly (almost 80%) covered by plantations of radiata pine (*Pinus radiata* D. Don). This had been converted from degraded agricultural land and native *Eucalyptus* forest nearly eight decades before. Some agricultural and pasturelands were distributed in small patches among the forest blocks and other pine species, *Eucalyptus spp*, *Prunus sp*, and *Ulmus spp* which were present in the forest. *Salix spp*, *Populus nigra* var *Italica*, *Casuarina spp* and Tussock grass species were common woody and non-woody vegetation along the rivers of the study area.

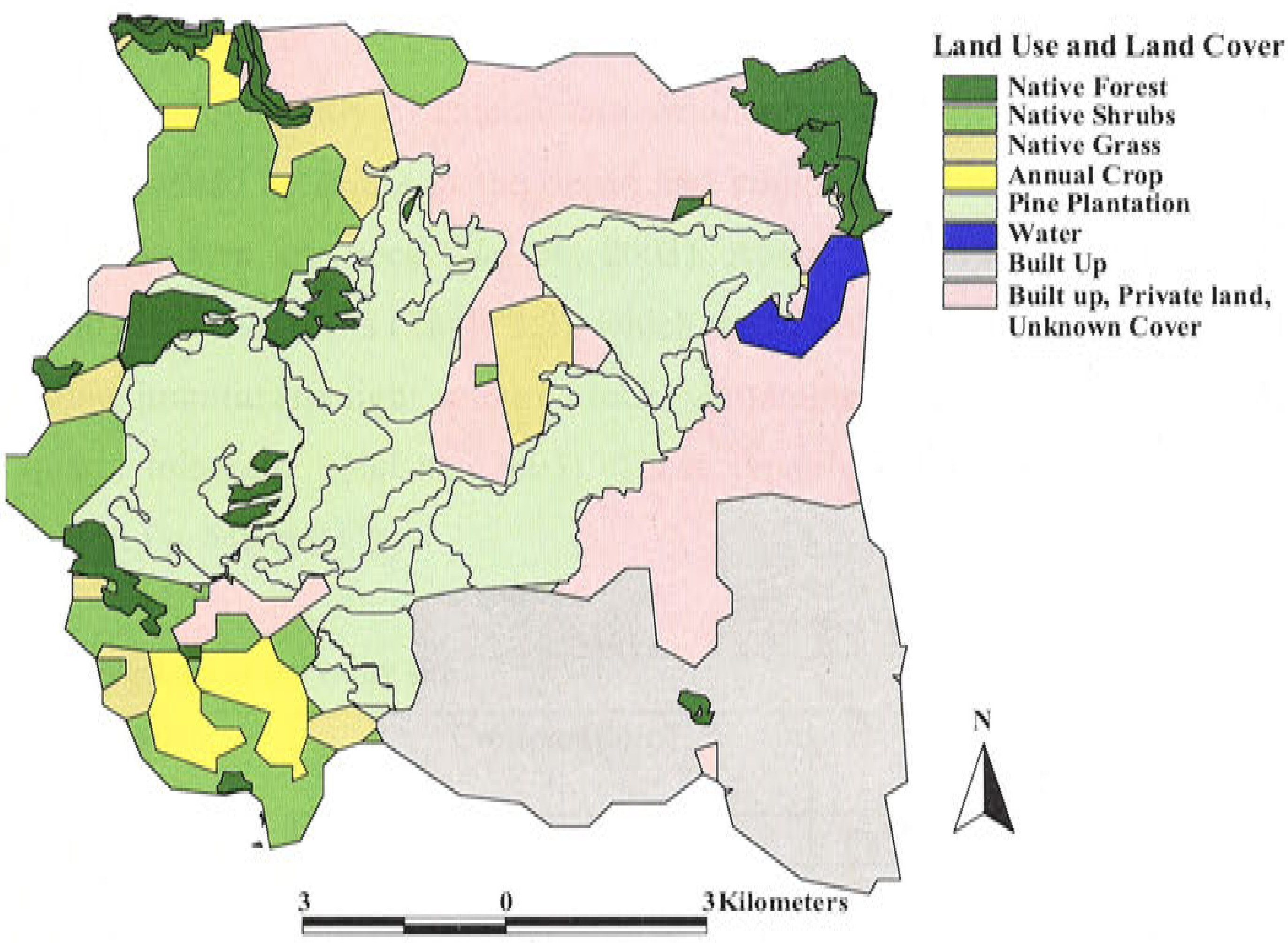


Figure 3.4. Land use and land cover of the study area (2002)

Figure 3.4 shows the land use and land cover of the study area, including the adjacent area, in 2002, prior to the bushfire event. This map was created using a combination of the clip, overlayed and merge commands of ArcGIS. The data and information from land coverage data sets mapped by NSW National Parks and Wildlife Service (NPWS, 2000, 2002), and a land use and land coverage map from Geoscience Australian, were used to create the land use map of the study area. Native forest and shrubs were distributed as small patches throughout the catchment and covered about 1300 ha of the study area (Figure 3.4).

3.4.2 Geomorphology (Geology and Soils)

The geology of the study area is Ordovician or late Silurian, consisting mostly of Laidlaw and Deakin Volcanics. These were subsequently covered by limestone (Lindsay, 1999). As a consequence, the soils are old, and the most soluble minerals and nutrients have long since been dissolved and leached away to streams (Lindsay, 1999). Geologically, the study area is mostly located on uniform limestone and rhyolitic rocks which cover almost 97%, that is, 10222 ha out of 10477 ha, of the area (Table 3.2 and Figure 3.5). Limestone, comprised predominantly of calcite, is a sedimentary rock It consists of eroded materials that are deposited as layers in the ocean and compressed through time, until the bottom layers slowly turn into rock (Nelson, 2003). About 51% (5369 ha) of the study area is covered by rhyolitic rocks (Table 3.2), which are of volcanic origin. The rhyolitic rocks are crystalline, granitic and light coloured rocks containing microcrystalline potassium feldspar and quartz minerals (Nelson, 2003). These types of rocks are rich in K and Na and deficient in Fe, Mg and Ca.

Table 3.2. Geology of the study site

Period	Composition	Common	Area	
			ha	%
Late Silurian	Ignimbrite tuff/ Limestone	Paddy river Volcanic	4853	46
Late Silurian	Rhyolitic	Volcanic	5369	51
Late Ordovician	Greywacke/shale	Nungar Beds	116	1
Mid/Late Silurian	Sandstone	-	43	0.4
Tertiary	Gravel	Silt	96	1
Total	-	-	10477	100

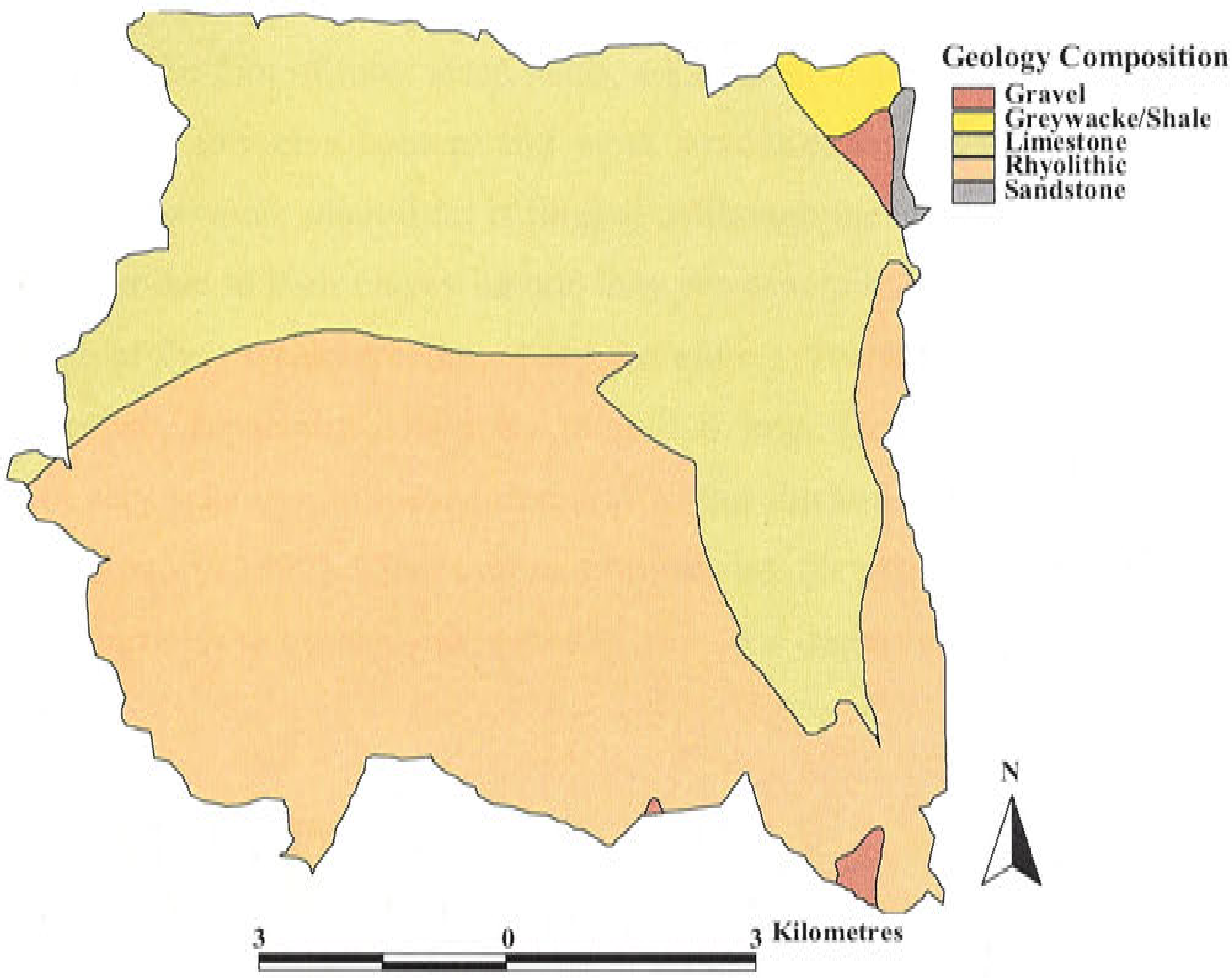


Figure 3.5. Geological composition of the study area

The study area mainly has a sandy or sandy loam surface containing small broken rocks (A horizon), and at a depth of 30 cm is underlain by yellow clays (B horizon). With reference to the Great Soil Group (Stace *et al.*, 1968), these soils are classified as Yellow/Brown/Red Duplex soils (Table 3.3). Duplex and Yellow Earth soils are the major soil types of the study area, occupying almost 97% (Table 3.3 and Figure 3.6).

Duplex soils can generally be divided into yellow, red, dark brown and grey soils based on the colour of the subsoil (Belford and Gregory, 1992). The Duplex soils group is common in southern and western NSW, in areas adjacent to the ACT, and these soil types also cover most of Australia's agricultural lands. Belford and Gregory (1992) reported that between a half and two thirds of the 19 million hectares of agricultural lands in southwest NSW with medium and higher rainfall are occupied by Duplex soils. These soils have a distinctive texture contrast between the top layer (surface soil) of sandy soil and the subsoils, which are generally clayey soils.

Duplex soils also cover much of the tablelands and stony plains of NSW and ACT and they are distributed at the foot of most steep lands, adjacent to lower land. As these soils have a sandy surface with low clay content and weak structure, they have a low water holding capacity, especially where plant litter is limited. Although the subsoils can often store large amounts of water due to their clayey nature, they are generally unable to supply moisture to plants because of their weak structure. They therefore provide very limited opportunity for vegetation growth, especially where the rainfall is low. These characteristics also make Duplex soils very sensitive to mechanical traffic and the soils easily undergo compaction (Belford and Gregory, 1992). Clear-cutting or removing the vegetation in any way will also cause the soil particles to be easily detached by raindrop impact and transported by runoff.

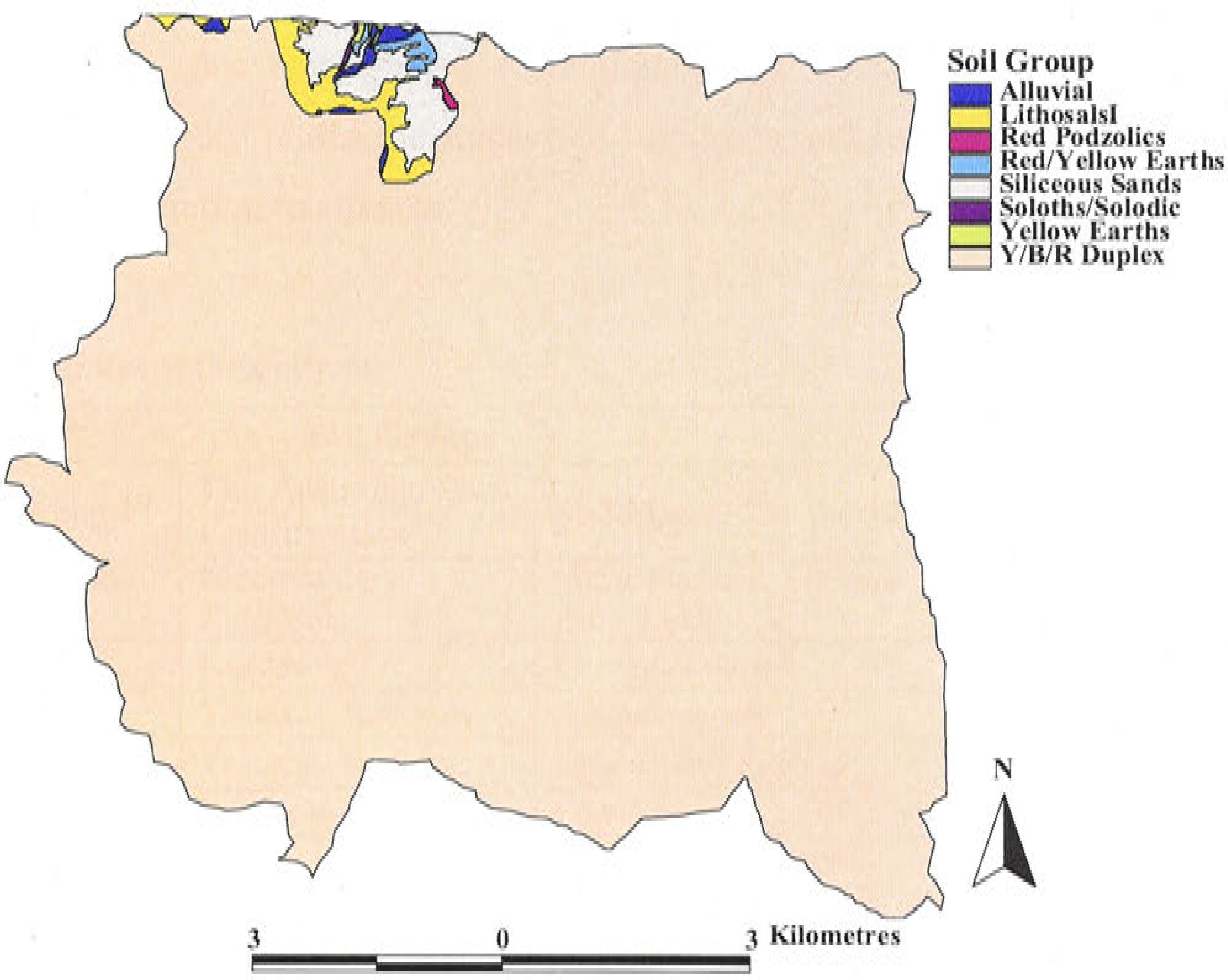


Figure 3.6. Soil map of the study area

Some soils in the flood plain of the Molonglo River and adjacent to major watercourses in the study area are relatively rich black soils; these soils cover <0.2% of the area (Table 3.3). Siliceous Sands also cover less than 2% of the area. These are mostly finer sands found around the Molonglo River and the sides of hillslope. These soils vary in colour and have a very deep profile, with organic matter accumulations in the A horizon (Sleeman and

Walker, 1979). Soloth soils originating from siliceous rocks, contribute a very small area (almost 5 ha) in the north of the study area.

As discussed in Chapter 2, several factors affect the interaction between soil and water and hence influence the formation of runoff. Soil type, soil characteristics such as texture and organic matter, the amount and duration of rainfall, vegetation cover and topographical factors (slope gradient and slope length) are the main factors influencing this interaction and its consequences in terms of soil erosion and sedimentation. Subsequent to the January 2003 bushfire, the soils of the study area exhibited four important characteristics that predispose them to high rates of erosion. These characteristics were: (1) sparse vegetation coverage of trees; (2) textural contrast profiles that are highly dispersive; (3) weak structure (as a result of overuse by previous forestry operations); and finally (4) compacted cycling and walking tracks (due to excessive recreational use). These hard soils, especially the surface soil, seal readily under the impact of raindrops and intensive rainfall, leading to erosion and sedimentation to streams.

Table 3.3. Soil groups of the study site

Soil Groups			**Area**	
Great Soil Group [1]	The Australian Soil Classification [2]	Soil Map of the World [3]	ha	%
Yellow/Brown/Red Duplex	Chromosols, Kandosols	Eutric Planosol, Luvisol, Albic Luvisol	10144	97
Yellow Earths	Kandosols	Chromic Luvisol	5	0
Siliceous Sands	Tenosols, Rudosols	Albic Arenosol	168	2
Lithosols	Tenosols, Rudosols	Lithosol and Regosol	109	1
Alluvial	Rudosols, Tenosols	Fluvisol	26	0.2
Red/Yellow Earths	Kandosols	Orthic Acrisol, Luvisol, Chromic Luvisol	21	0.2
Soloths/Solodic Soils	Kurosols	Orthic Luvisol	5	0
Red Podzolics	Kurosols	Luvisol	5	0
Total			10477	100

Source: [1] Stace *et al.* (1968); [2] Isbell (1996); [3] FAO-UNESCO (1990)

Cutting the slope, removing the soil, filling in the depressions and compacting the soil for road surface protection are the most common activities impacting on the soil during road construction. The resulting soils are known as 'anthropogenic soils' (Dudal *et al.*, 2002), that is, their surface and subsoils have undergone human-induced disturbances. Road construction and timber harvesting processes significantly influence soil profile properties.

However, it is more difficult to predict the level of interaction between soil and water after these anthropogenic changes, compared with natural soils where the properties reflect the soil classification. The anthropogenic influences may make the soil more easily eroded and transported by runoff, especially during and for a few years after road construction. The soils on the cut and fill batters of Stromlo Forest roads are, therefore, more likely to be eroded because of a range of factors, that is, their soil type, the construction and maintenance processes they have undergone and the removal of vegetation cover during construction.

3.4.3 Climate and Rainfall

The climate of the study area and most of the rest of the ACT is alpine, with warm to hot and relatively dry summers and cool to cold winters (Baskin, 1996). According to the Bureau of Meteorology (2004) the climate of Canberra is strongly influenced by bands of high pressure located around the globe at about 30-40°S, known as sub-tropical ridges. This system is located over southern Australia, including the Canberra region, during the summer, resulting in warm and hot weather with winds generally from the east through to the northwest. The system is located across northern Australia during the winter resulting in adverse effects on the weather of the Canberra region because of the westerly winds associated with cold fronts (Bureau of Meteorology, 2004).

Among the climatic parameters, rainfall is the most important variable as a cause of soil erosion. Generally, changes in elevation, temperature, topography, location, amount of vegetation cover and impacts on ecosystems act to vary the effects of rainfall. According to the Bureau of Meteorology (2002), the Australian rainfall pattern is mostly seasonal in character, with a mainly winter rainfall regime in the south and a summer regime in the north. Although the Australian Capital Territory region is located in the south east of Australia and the rainfall pattern should follow that of the southern region, the rainfall varies from year to year and season to season, ranging from dry periods to intense rainfall. The Bureau of Meteorology (2004) reported that the average annual rainfall of the Canberra region is about 629 mm with an average of 108 rainy days per year; the wettest month is October with 65.3 mm, and the driest is June with 39.6 mm (Table 3.4).

Table 3.4. Average rainfall and maximum and minimum temperature of Canberra region

Item \ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average Rainfall	61.5	53.6	52.6	49.5	48.6	39.6	42.0	47.2	52.6	65.3	63.3	53.1	629
Mean Maximum Temperature	27.7	27.0	24.4	19.8	15.3	12.1	11.2	12.9	16.0	19.2	22.4	26.0	19.5
Mean Minimum Temperature	13.0	12.9	10.7	6.6	3.2	0.9	-0.2	0.9	3.1	6.0	8.6	11.2	6.4
Average Temperature	20.0	20.0	17.5	13.2	9.3	6.5	5.5	7.0	9.5	12.5	15.5	18.6	12.9

Source: Adapted from Bureau of Meteorology (2004); Gungahlin Weather Centre (2004)

3.5 Forest Management Systems

Stromlo Forest Management Area (SFMA) was managed partly as an industrial pine plantation forest, and partly for public recreation. Improving the land uses and reducing the land degradation of the area close to the capital city of Australia were among the main strategies behind its establishment in 1915.

The origins of the Stromlo Forest Management Area (SFMA) and the adjacent Uriarra and Pierces Creek forest areas reflect the history of the ACT. Initially the area was associated with the local Aboriginal people, and then in the 19th century with settlers (mostly European pastoralists) whose practices degraded the landscape (forest and pasture lands). The city of Canberra was developed mainly after 1925, and a modern multiple-use plantation was established. Management of the study area attempted to address three major objectives: environmental objectives such as controlling wind erosion on over-grazed land and providing an attractive landscape for the city; industrial wood production; and recreation activities. Baskin *et al.* (1996) noted the increasing urbanisation of the rural lands around Canberra and that this was a major problem in maintaining the areas' landscape values. The study area is under heavy and increasing pressure from the growth of Australia's capital city (Canberra) and the effects of urbanisation. The management plan for the area, therefore, must have enough flexibility to cater for the different objectives and should be supported by some strong scientific evidence to safeguard the environmental objectives under the forest management strategy.

Before the major bushfire of January 2003, the SFMA was under the third rotation of the pine plantation. The 18^{th} January bushfire event had severe impacts on both the community and environment. The public and the residents of the suburbs close to the forested area raised many questions related to the SFMA, particularly 'how far should the forest management area be located from the residential area?'. The severe physical and environmental impacts of the bushfire increased public awareness and emphasised the role of the community in determining the management plan of the area. Decisions about managing the rehabilitation of the fire-affected area mostly reflect the concerns of the community about having a forested area close to the urban area. For example, the ACT Government (2003) stated that because the Stromlo Pine Plantation had been one of the city's main areas for recreational activities over many years, and almost all of the forest had been damaged by the bushfire, there was a strong case for restoring the SFMA. Ultimately, the SFMA was not re-established to pine plantation, but to less dense vegetation designed for recreational and fire prevention activities (ACT Government, 2003).

The ACT plantation was established in 1915 on Mount Stromlo with *Pinus radiata* and small plantings of *Cupressus spp* (Carron, 1988). Planting continued in the 1920s and 1930s in most areas of Stromlo and adjacent land around the Cotter River where the forests, pasture and agricultural lands had been degraded by new settlers and natural events like fires at the end of the 18^{th} and early 19^{th} centuries (Jacobs, 1939; Baskin *et al.*, 1996). Most of these plantations were destroyed by fire events in 1938 and 1952 but were replanted mostly with *Pinus radiata* (Baskin *et al.*, 1996). Although most of the woody and non-woody native vegetation has been removed, there are still many native trees, shrubs and grasses that can be found throughout the study area, especially in the lower level of the canopy.

Figure 3.7, reproduced from an original map supplied by ACT Forests, illustrates Stromlo Forest's compartments. All compartments were planted with pines (mostly *Pinus radiata* D. Don), beginning in 1915.

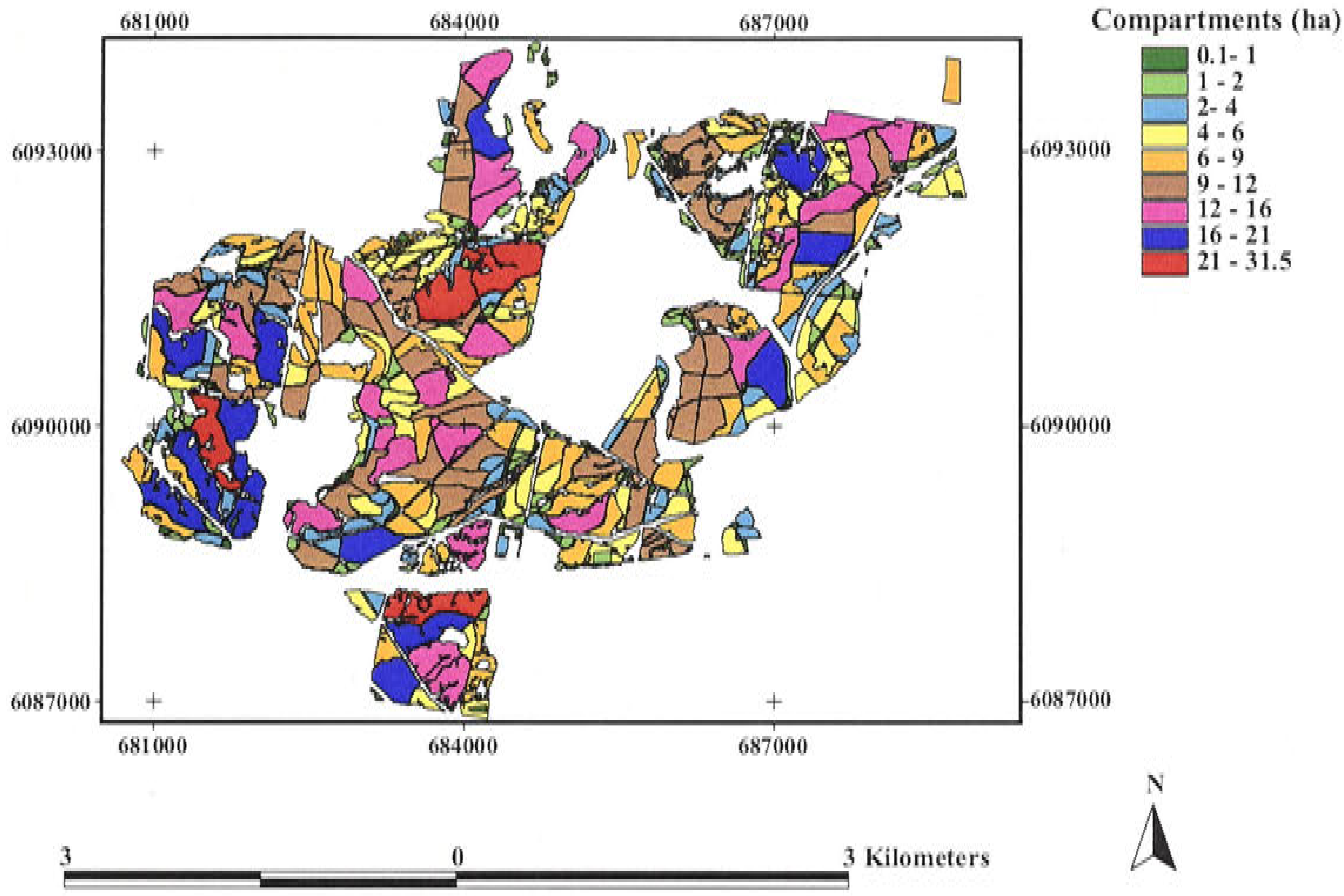


Figure 3.7. The location and size of Stromlo Forest Compartments (2002)
Source: ACT Forests, 2002

3.5.1 Forest Roads

Stromlo Forest road network was the basis of both industrial timber production and recreation activities. Continuous access on these roads is mostly related to technical issues and the safety situation and condition of the roads. However, the location of the roads in the landscape and on stable terrain is very important to both their use and sediment production from the road prism. The forest road system and its impacts on environmental values like soil and water are major areas of concern for forest management systems. Management of the roads to mitigate and control their negative effects on the soil, with consequences for water quality impacts, needs to be based on technical information on the roads such as the characteristics of the roads, location of the roads in the landscape, construction and drainage structures and also the status of maintenance. Unfortunately, most historical information concerning the road systems is not available because the 2003 fire event destroyed all management information stored in the ACT Forest Headquarters.

The Stromlo Forest Managed Area (SFMA) is serviced by almost 264 km of unsealed forest roads (A. Winter, ACT Forests, pers. comm., 7 January 2003), excluding about 40 km of public roads (asphalt) and walking tracks, which are located in the adjacent area and out of the forest compartment area (Figure 3.8). They cover about 6 precent of the SFMA by area and result in a road density of 120 meters per hectare. These roads range from well designed (and re-designed) and maintained roads to temporary roads and snig tracks, which are seldom graded and lack maintenance. Most SFMA roads were constructed in the 1950s to 1970s and are called 'existing forest roads' in this research, because of the lack of reliable technical information related to the age, road construction and maintenance history of the roads.

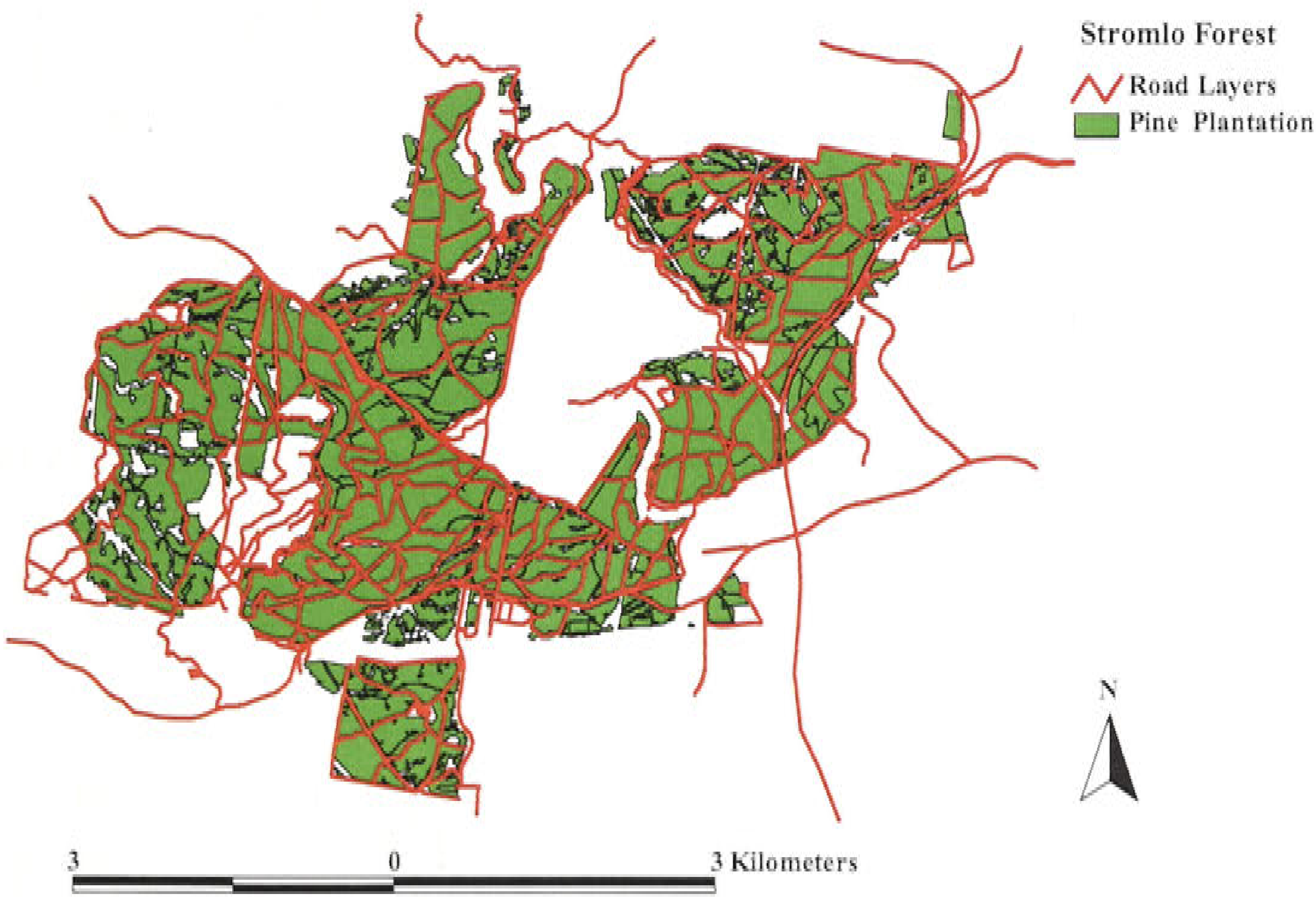


Figure 3.8. Stromlo Forest plantation area with road network (2002)
Source: ACT Forests, 2002

Figures 3.8 and 3.9 show the pine plantation area, forest road network and application classes in the study area. As shown in Figures 3.9 and 3.10, public roads, which are usually sealed roads, are used as the main roads to access Stromlo compartments (Stromlo Blocks) for all forestry activities such as timber harvesting, wood transportation, planting and fire fighting. Most roads (minor access and tracks) distributed in the pine plantation compartment areas are linked to the major access and ultimately to public roads.

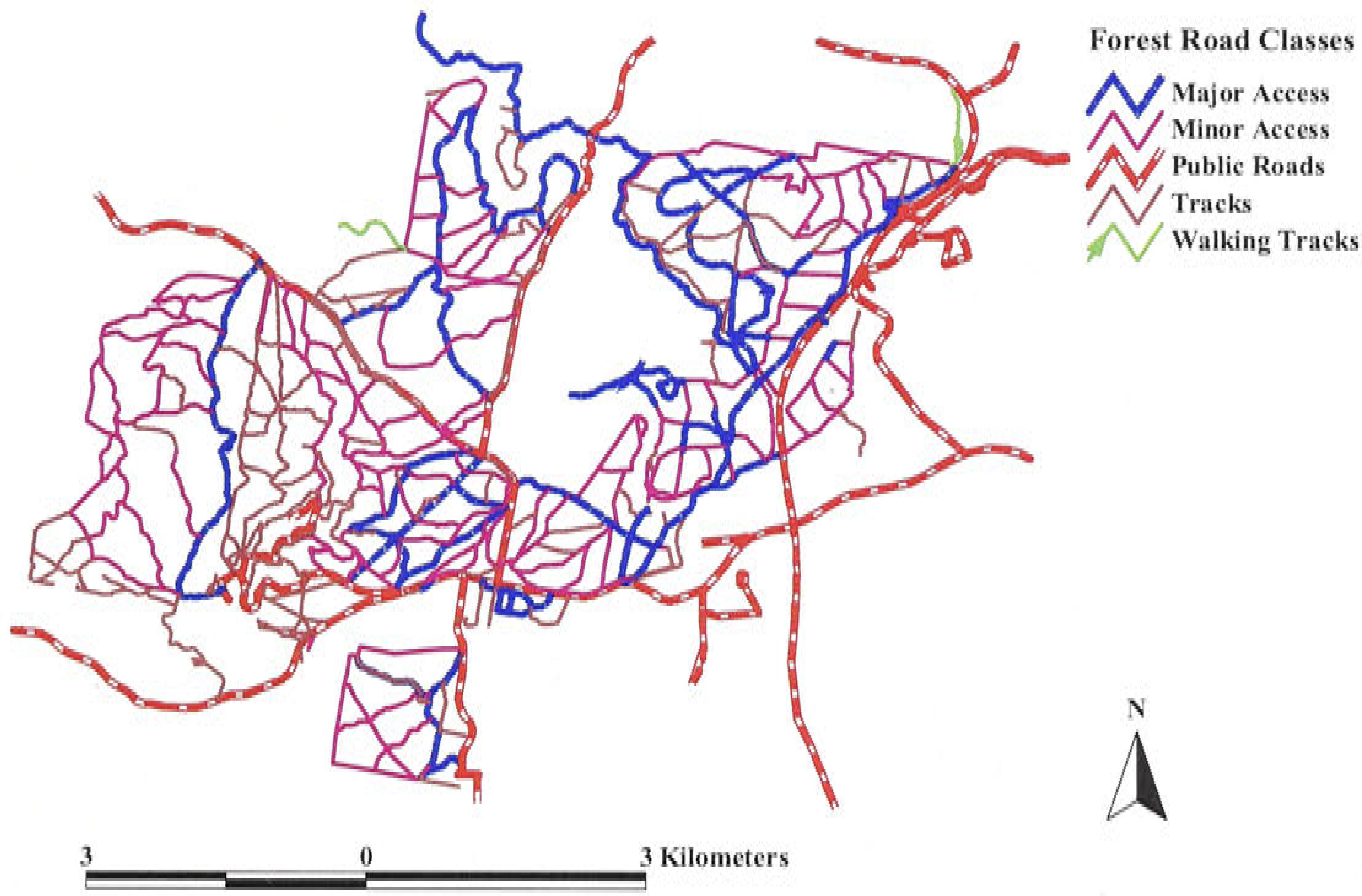


Figure 3.9. Forest road network and types of Stromlo Forest (2002)

Source: ACT Forests, 2002

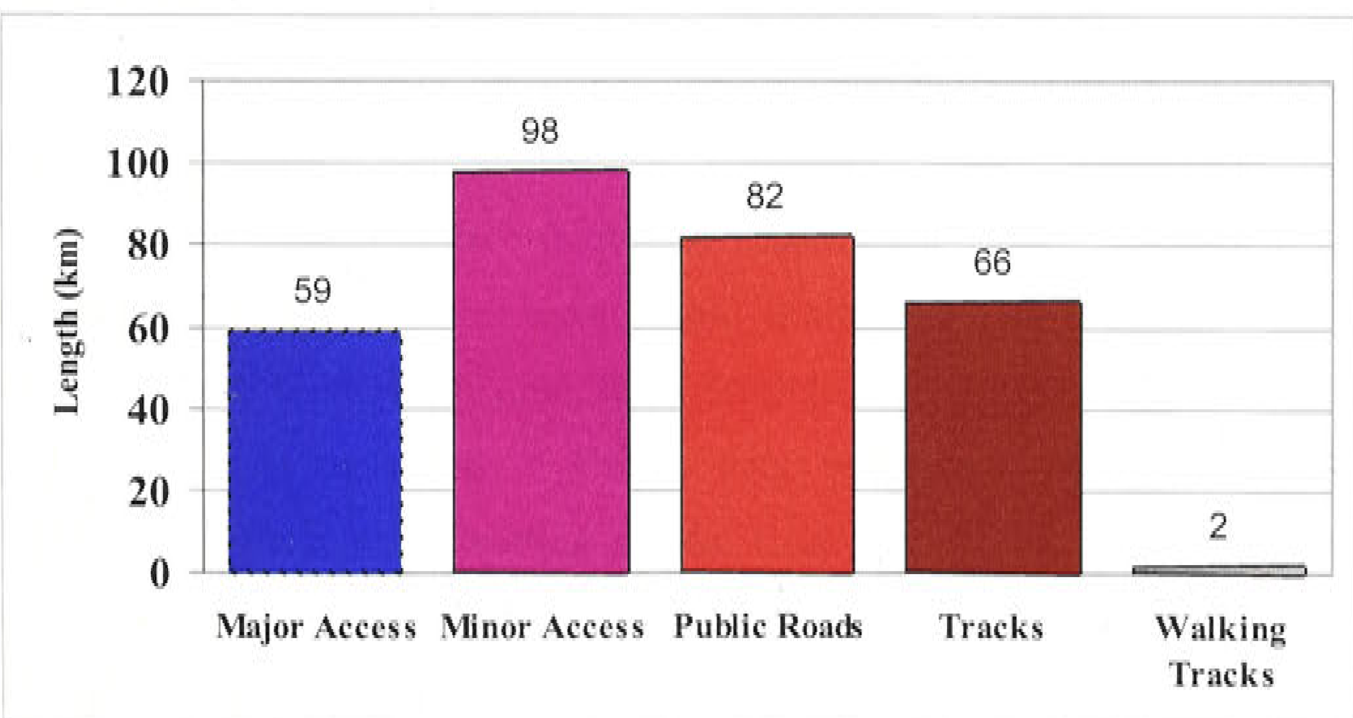


Figure 3.10. Distribution of length and type of the forest roads in the Stromlo Forest; categories as applied by ACT Forests

As can be seen from Figure 3.10, major and minor access roads are the main types of roads servicing Stromlo Forest and adjacent areas, representing 19% (59 km) and 32% (98 km), respectively. Tracks are generally built for temporary use for collecting timber and transferring logs to the main roads during forest operations. About 22% (66 km) of forest roads in the study area are classified as 'tracks' and were made to give access for harvesting operations, both thinning and final harvesting, and other forest management practices of short duration like site preparation and fire fighting. About 82 km of the roads serving the pine forest and adjacent area are public roads. These roads are mostly used for public transportation to some ACT suburbs (for example, Tuggeranong Parkway and Cotter Rd) and to areas of NSW (for example, Uriarra Rd) (Figure 3.9). However, some public roads directly service the Stromlo Forest area like Mt. Stromlo Road, built to access the Astronomical Observatory and some pine compartments around Mt. Stromlo, and are also used in the processes of forest practice and management activities.

No quantitative data were available on the intensity of forest road use prior to the study, as a consequence of the total loss of ACT Forest records in the January 2003 bushfire. However, heavy traffic use had been light by typical production forestry standards, as a consequence of both forest age structure and management priorities.

Forest Road Maintenance

Most Stromlo Forest road network surfaces consist only of native soil (see Appendix B, Table 3). This earthen surface frequently requires maintenance to maintain access, protect the road surface against sheet erosion, and minimize the adverse impacts on water quality. On the basis of field observation, most Stromlo road network maintenance was limited to grading the road surface by a Grader once or twice a year. This operation was only implemented when wheel rutting on the road surface was sufficient to cause water to remain on the road travelway, with consequent access problems. Because most of the road network, that is, tracks and minor access roads, were only trafficked during forest operations, road maintenance was generally limited to keeping the major access roads serviceable.

3.5.2 Pine Plantation Establishment and Site Preparation Activities

Pines were planted in the Stromlo area for the first time in 1915 on disused, over-grazed agricultural land which contained some forest remnants (Jacobs, 1939; Carron, 1988; Baskin *et al.*, 1996). However, clear-cutting for industrial timber harvesting removes the vegetation canopy that protects the soil, leaving the soil bare and under direct pressure from raindrops and sheet erosion losses. Soil may suffer compaction by machinery and finally, the delivery of litter to the topsoil is decreased. These impacts can sometimes be exacerbated during pine plantation establishment, especially during site preparation. Logging, burning, digging, and creating earth mounds along contours are common activities in site preparation that cause some changes in soil structure (Costantini and Loch, 2002). Soil may wash away during rainfall and also be transported to streams by runoff.

3.6 Recreation Activities and Their Impacts on the Environmental Values

The Uriarra-Stromlo valley is one the most attractive areas in the Canberra area because of its beautiful and unique landscape. The ease of access and its short distance from the city – 10 km from the city centre and very close to the residential areas in the western suburbs – have made this area much more attractive to the public compared to other areas of the ACT. These factors make the area one of the most important cultural landscapes, of historical interest because of its relevance to the Aboriginal people and early settlers, and also the high level of recreational use by the public.

Bush walking, camping, mountain bike riding, motorbike racing and horse riding are some common recreational activities carried out in the Stromlo Forest. Motorbike and 'mountain bike' riding on the forest floor over routes formed by continuous and extensive riding on steep terrain have caused some sheet and gully erosion. Although this research did not study the effects of the recreation activities in the study area, several gullies on walking tracks and bike routes were seen during field observation, especially around Mount Stromlo.

3.7 Bushfire

Australia's landscape is well known to have been modified by periodic bushfires that are difficult to predict and control. Some bushfires are natural events (wildfires) and these occur regularly in the Australian context, especially in native forest ecosystems. Many large or widespread bushfires have been recorded throughout the Australian states in the last half-century. For example, two bushfires in 1964-65 in the Blue Mountains and Tumut Valley of NSW burnt nearly 330,000 ha of grassland, forest and residential areas. On the 18^{th} of January 2003, the ACT faced one of the worst and most tragic bushfire events in its history. The fire burnt almost all of Stromlo pine plantation and damaged private and public property, as well as causing the deaths of four people (Figures 3.11 and 3.12).

Figure 3.11. Removing the burnt trees and site preparation for bushfire recovery around Mt. Stromlo after the 18th January 2003 bushfire. The rows are the clear-cut burnt timber bulldozed together. The burnt-out buildings of Stromlo Observatory can be seen on the top of the ridge.

Source: Author's photograph, March 2003

Although some pine plantation compartments of the study area had already been burned in a fire in 2001, the 2003 bushfire destroyed the area completely. Because of that and site clearing operations, most pine compartments were closed for safety reasons and it was impossible to gather field data for 6 months after the bushfire event. The forest situation and characteristics and fauna and flora had been completely changed. The new situation made the roads worse, especially during and after heavy rainfall and storms at the end of January and in early February 2003. For all of these reasons, the methods of sampling and gathering data had to be changed (see Chapter 4).

Figure 3.12. Site preparation for bushfire recovery around Mt. Stromlo and adjacent area after the 18th January 2003 bushfire

Source: Author's photograph, March 2003

Figures 3.13 and 3.14 are from the Landsat 7 and Spot 4 images of the study area. Figure 3.13 shows the situation of the study area before the 18th of January 2003 bushfire. The original image is from NSW National Parks and Wildlife Service and covers all of the ACT land and territory and the Boorowa region in the NSW. The study was clipped and extracted and the layers (image bands) composed for creating the colour map using ERDAS, IDRISI and ArcGIS software.

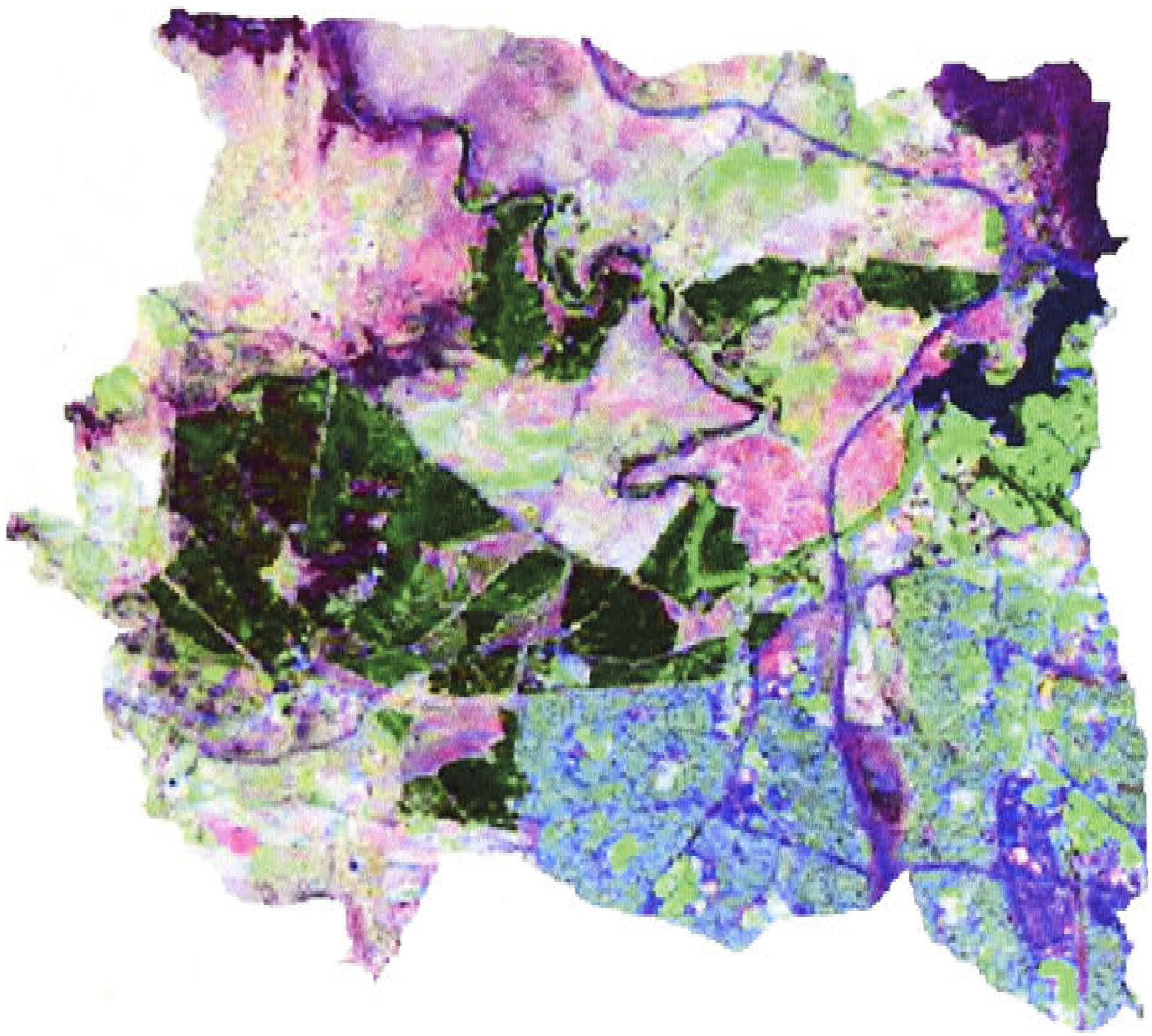


Figure 3.13. Satellite image (Landsat 7) of the study area in 2002 before the 2003 bushfire

Figure 3.14 shows the situation of the study area on 5th of February 2003, after the 18 January bushfire. As can be seen from the figure, most of the Stromlo Forest and adjacent native bush and grasslands were severely affected by the bushfire event. According to McLeod (2003) and ACT Government (2003), the affected area and private land and properties (including the people affected) were or will be re-established and recovered in three stages: immediate recovery actions (focusing mostly on affected people and properties, from 18th to 27th of January); after the state of emergency; and, finally, longer term recovery for 2003-2004 action. The ACT and Australian governments have spent millions of dollars on the recovery plan in the period since the bushfire.

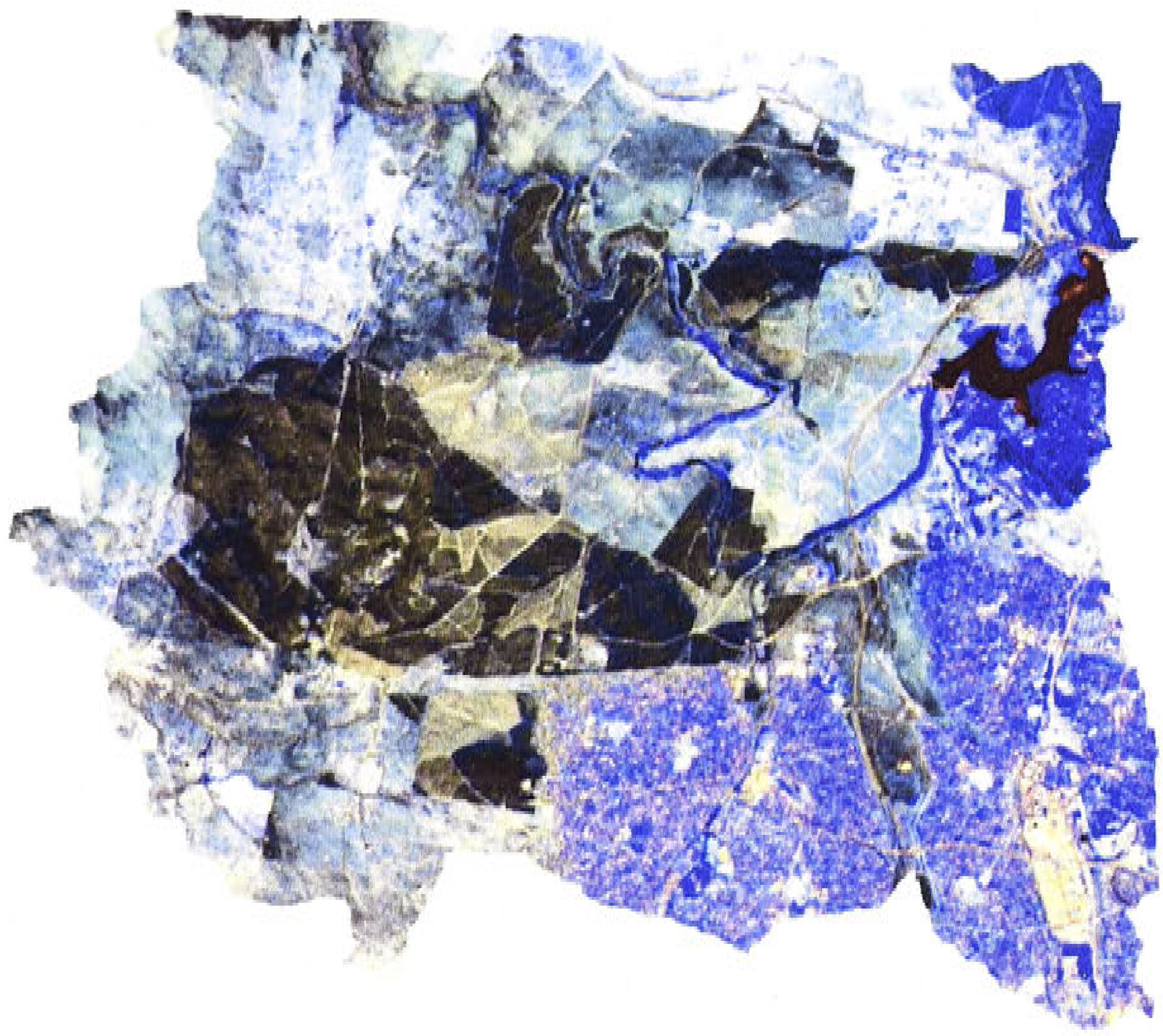


Figure 3.14. Satellite image (Spot 4) of the study area in 2003 after the 18th of January 2003 bushfire

3.8 Summary and conclusions

Stromlo Forest (pine plantation) was selected as the study area because it met all the criteria for applying the chosen required risk assessment approaches to the impacts of forest road systems on water quality. The information and data related to the study area explained in this chapter provide a background and framework for the approach to forest road risk assessment used in this research. The chapter has also provided a brief explanation of the history, use, roading and management system of the Stromlo Forest, and the changes in vegetation cover in the study area because of bushfire events, as background for risk assessment, field assessment and data gathering described in Chapter 4.

Chapter 4
Methodology and Data Sets

4.1 Introduction

The hypothesis of this thesis, explained in Chapter 1, is that 'by analysing the attributes of an unsealed forest road and its surrounding terrain, it is possible to evaluate the risk that erosion from the surface of the road, or associated with the road drainage structures, will deposit water-borne sediment into an adjacent stream'.

The major objective of this study is to devise a method for predicting the probable impacts of forest roads on soil and water, by combining spatial attributes of the drainage structures with terrain attributes of the surrounding land. The material presented in this chapter describes the methodology and data gathered for assessing these impacts. The research has focused on developing a simple and practical method for assessing the risks posed by unsealed forest road systems to water quality.

Table 4.1 summarises the methodology used in the study, both in general terms and in terms of its specific application in this study. The key methodological stages of this study were:

1. Experimental approach, design and sampling strategy;
2. Terrain modelling and analysis;
3. Forest road analysis;
4. Hydrological analysis, including GIS-based and statistical modelling;
5. Developing an erosion risk model using logistic regression; and
6. Risk assessment and mapping, including predicting and mapping soil loss for the study area and the roads.

Each of the elements of the methodology is described in the following sections.

Table 4.1. Summary of the methodology followed in this study

General methodology	Application in this case study
1. Experimental Approach, Design and Sampling Strategy • Estimate sample size • Conduct road inventory (road, drainage and erosion characteristics) • Map road drainage, rill and gully erosion	1. Develop experimental approach, design and sampling strategy 2. Identify study area – Stromlo Forest, ACT, Australia 3. Conduct field survey • Estimate sample size • Develop road inventory forms • Record road characteristics • Record road drainage structure characteristics • Record rill and gully characteristics 4. Partition data into 'development' and 'validation' data sets for model development and verification, respectively
2. Terrain Modelling and Analysis • Obtain or create Digital Elevation Model • Develop Digital Terrain Model (DTM) from DEM • Conduct Terrain Analysis (TA): o Create Terrain layers & attributes o Conduct slope position analysis	1. Obtain topographic maps, DEM, & satellite imagery of the study area 2. Create a DEM layer for pilot study and test the possibility of using DGPS 3. Conduct terrain analysis: • Prepare the DEM for analysis • DTM using Relief Analysis to create terrain attribute layers • Slope position analysis and topographic or landform classification • Calculate slope length, slope gradient, and aspect layers • Estimate slope Stability Index (SI)
3. Forest Road Analysis • Map road network • Road slope position analysis • Assemble spatial data sets • Create road database	1. Digitise the road network from spatial information • Verify road network and map drainage location 2. Assess erosion risk associated with road and drainage structures • Classification of road drainage structures and road layers 3. Conduct road slope position analysis 4. Extract relevant terrain attribute values 5. Assemble spatial data sets and create single integrated data set
4. Hydrological Analysis • Delineate watersheds • Model flow pathways • Assess road-to-stream hydrologic connectivity	1. Conduct stream and watershed delineations • Create stream networks • Create basin and sub-watersheds 2. Model the flow pathways length (road-to-stream hydrologic distance) using five GIS-based models 3. Assess road-to-stream hydrologic connectivity and analysis using statistical and GIS-based approaches • No connection • Gully connection • Diffuse connection
5. Development of Rill & Gully Occurrence and Road-to-Stream Connectivity Risk Models • Data preparation • Develop models, Conduct logistic regression & ANOVA • Test and validate the models	1. Data preparation 2. Develop models by analysing the data using logistic regression and ANOVA • Apply stepwise procedure for selecting the independent variables best correlated to the dependent variable • Built statistical model for road surface & outlets of the road drainage structures and road-to-stream hydrologic connectivity, separately 3. Test the models • Test the fitness of the models to data by applying the Hosmer & Lemeshow goodness-of-fit test • Apply the Receiver Operating Characteristic Curves (ROC) test • Apply residuals plots and analysis 4. Validate the model • Model the probability of occurrence of rill & gully • Apply the model using both sample and population data in order to compare: • The error • The accuracy of the prediction • Fit model to data
6. Risk Assessment and Mapping • **Identify the Risk** • Mapping rills and gullies • Apply RUSLE to study area • **Analyse the Risk** • Establish risk criteria • Rank risks according to criteria • **Create Risk Maps** • Create a risk map • Integrate the risk assessment into a consolidated map	1. Identify risk • Mapping rills and gullies • Estimate the RUSLE factors using GIS-based application • Apply the RUSLE to predict soil loss of hillslope and forest roads 2. Analyse the risk • Establish risk criteria • Establish a risk matrix • Rank risk according to the criteria 3. Create risk maps • Create risk map for each component, as defined by significant variables • Integrate the qualitative and quantitative risk assessment into a consolidated map for study area and its forest road network

4.2 Tools

The study was conducted using a set of tools including GPS, GIS software packages – Arcview, ArcGIS, ERDAS, IDRISI, FGIS and MapWin – and statistical software – STATISTICA (V. 5.5 and 6), SPSS (V. 11.5) and JMPin. A Differential Global Positioning System (DGPS) was used for gathering data in the field. Before purchasing the equipment, different models were tested in order to determine which type or model of GPS was suitable for gathering accurate data in the field. An 'Ashtech' DGPS (Magellan Corporation, 1998) was selected for collecting field data because of its accuracy, number of features and attribute information. The Ashtech package includes a handheld controller, GPS receivers (rover and base) capable of providing sub-metre accuracy, interconnecting cables, a GPS antenna and Reliance software for downloading, processing, exporting, correcting and transferring the collected data to a GIS (Magellan Corporation, 1998).

The advantages of using a combination of DGPS and GIS tools to gather field data from the road prism, and perform assessment and analysis, are: high accuracy of establishing spatial location of drains and roads; lower incidence of data transfer errors because of direct digital entry of most information; ease of data manipulation and analysis using GIS and spreadsheets; and the field data can easily be kept and used in conjunction with Digital Terrain Modelling data to evaluate specific future cases. DGPS and GIS can also make information gathering easier, more accurate and cheaper than paper collection.

4.3 Experimental Approach, Design and Sampling Strategy

The approach adopted by this study was to assemble a data set representative of the study area, and then to partition that data set into development and validation data sets for model development and verification, respectively. Creating development and validation data sets is the standard means of developing and testing predictive models. Small and Edelstein (1997) stated that, in almost all data mining applications, the data is divided into at least two sample subsets; 'development' and 'validation' data. The development data is used to develop a model and estimate the model parameters and the validation data is used for model testing and validation.

4.3.1 Identify Study Area for Field Survey

The first step in conducting this study involved finding a suitable area for gathering data in order to test the hypothesis of the study. Stromlo Forest, ACT, Australia, described in Chapter 3, was selected as the case study area.

4.3.2 Experimental Design and Field Survey

As conducting a field survey on the entire forest road network of about 300 km of the study area would have been too expensive and time-consuming, sample segments of the road network were selected using stratified random sampling. A road segment is a section of road transect that, generally, defines a continuous length of road between two road drainage points. Each road transect in the study area consisted of many segments, up to 385 m in length.

Prior to the study, there was no information from the field about the number of drains, or drain positions, on the forest roads. Nor was it known beforehand which of the parameters that were collected in the field would prove to be the most useful for model building. This precluded developing a sampling strategy based on the acceptable level of error for a single parameter. Therefore, it was difficult to predict which road characteristics or parameters and terrain attributes should be used as the basis for determining the sample size. Consequently, a stratified random sampling strategy, based on the time and financial resources available for sampling, was used to collect the information about the parameters and variables of the population that might be useful for model building. This sampling process will be called the 'field survey' in this thesis. The aim of field survey was to collect as much data that might be useful for building a model from as many variables as time and money permitted.

Under the stratified random sampling method used in the field surveys, each element (that is, section or road transect) in the population (that is, 300 km of road network) had an equal chance of being sampled. Stratification increases precision without increasing sample size (Patten, 2002; Pavkov and Pierce, 2003; Bass, 2005). Sample stratification involved two steps: (1) dividing the population of sampling units into population sub-groups, called strata; (2) objectively selecting a sample of predefined size (n) in each stratum.

To do this, the entire road network of Stromlo Forest was stored as digital coverage in Arc/Info and ArcView GIS database. Data layers of road topographic position were used to define strata and consequently select road segments for the field survey. Road segments were stratified into three topographic positions – valley bottom, mid-slope and ridgetop – using the scheme developed following Wemple *et al.* (1996). Topographic position was used as the basis for stratification by Montgomery (1994), Wemple *et al.* (1996) and Hatfield (2003), who identified it as the most appropriate basis for examining the selection of road network for detailed survey. Topographic position is recognised as an important variable in evaluating erosion processes in forest road system (Bloom, 1998). The methods used to assign slope position to each of three categories followed those developed by Montgomery (1994), Wemple *et al.* (1996), Hatfield (2003); all are described in section 4.4.2.

Factors Determining the Number of Measurement Sites

The main factors determining the number of measurement sites for the pilot study were time and the budget available for the survey. A total budget of approximately $6600 was available to cover DGPS and the use of a four-wheeled drive vehicle. For each segment, data collection involved observing approximately 6 drains and the associated road prism; the cost was estimated at around $65 for each km of road sampled. Consequently, the total length of road that could be sampled was around 102 km.

The actual road transect and segments to be surveyed were chosen from the survey population of the entire road network by allocating a unique number to each strata and then using a simple random-number generator to select representative road segments. The most common approach is to sample the same proportion of items in each stratum; this is termed proportional allocation. Therefore, the overall sampling fraction is:
Road sample size/Total road length = 102/307 = 0.332.

The consequent sample assignments are listed in Table 4.2.

Table 4.2. Distribution of the length of road sampled in each stratum

Road strata	Total (km)	Sample (km)	Allocation
Valley bottom	64	21	0.332
Midslope	162	54	0.332
Ridgetop	81	27	0.332
Total	307	102	0.332*

* Average allocation

The variance, standard deviation and standard error of the population and the field survey sample were calculated and compared (Table 4.3). Asphalt public roads were excluded from the statistical calculation, as they were not selected for the field survey. The comparison in Table 4.3 shows that the sample provides a good representation of the population.

Table 4.3. Statistical comparison of the population and sampled road network (length of road segments)

	Valid No. of road segments	Sum (km)	Mean (m)	Median (m)	Confid. -95.00%	Confid. +95.00%	Variance	Std.Dev.	Standard Error
Population	707	307	353.59	241.94	319.49	387.69	213309.6	461.85	17.37
Sample	313	102	324.62	249.78	293.30	355.94	79308.88	281.62	15.92

Table 4.3 shows that of the 707 road segments present in the Stromlo Forest area, 313 were selected to be sampled. This sample covered more than one third of the road length and included almost 30% of the drainage structures. Mean length of road segments in the population was 353 m, and in the sample 325 m. This was well within the 95% confidence interval; by using the finite population correction for large sample size, it is possible to

determine that an estimate of the mean within the same confidence interval could have been obtained using a sample of only 80 km of road. This suggests that the sample size used in the study, 102 km, was more than adequate.

4.3.3 Conduct of Field Survey, Road Inventories and Assessments

Develop Road Inventory Forms

Gathering data from the field using GPS requires associated pre-fieldwork preparation work. The features file should be designed, written and then uploaded into the GPS program through connecting a field handheld system controller to a PC.

The use of the DGPS and related software –Reliance – can be divided into four main steps:

1. Preparation, which includes uploading the feature files from a PC into a field handheld system controller;
2. Recording data in the field. The data can be a line, a point, or a polygon, and numeric or nonnumeric;
3. Data transfer, which includes downloading the recorded data from the rover and the base receiver by connecting the receivers to Reliance software.
4. Processing and exporting the data from the Reliance as a vector file into GIS software.

Application in this Case Study

For this study, a specific feature form was written for each road feature, covering all necessary field data related to that feature. The forms for each of the features are summarised in Appendices 1 – 4. The feature file was then transferred into the handheld controller prior to starting the recording.

Data Collection from the Field: Forest Road and Drainage Characteristics and Relevant Variables

The actual route of the forest road is one of the most important factors influencing the likelihood of negative impacts on the environmental values of the forested catchment. As described in Chapter 2, physical and topographic features – slope gradient, swamps, rock bluffs, debris slides and topographic position (crest, pit or depression) – all influence the likelihood of negative impacts from road location, design, construction and maintenance.

As explained previously, because of lack of data and information about the characteristics of the Stromlo Forest road network and its drainage structures, data were collected for all road and drainage characteristics and relevant terrain variables that may influence the risks to soil and water.

Spatially explicit field data describing road attributes and drainage structure characteristics were gathered using the Ashtech DGPS. The exact locations of sampled road lines were mapped in the field with the DGPS using a permanent base station located approximately 15 km from the study site. The base or reference station selected as the permanent position point was the workstation of CSIRO Forestry and Forest Products in Yarralumla, ACT. The collected data were then downloaded, processed, corrected, exported, and transferred to a GIS (ArcView) using the Reliance software of the DGPS. The final output of the process is a vector layer (Shapefile) showing the map of the road location on the ground.

Table 4.4 summarises the characteristics and type of data and variables collected in the field. Data were collected from the 102 km of roads selected for sampling to describe the road surface, cut and fill batters, road drainage structures, and rill and gully erosion and channel formation on the road surface and associated with the road drainage structures.

Table 4.4. Summary of the road features and variables assessed in the field

Features assessed	Variables	Scale
Road Surface	1. Two-dimensional slope gradient (in length and width)	Degrees and/or percent
	2. Road surface condition	Sealed and Unsealed
	3. Road use (traffic)	No traffic, occasional, very light, light, moderate and heavy traffic
	4. Road length and width	Metres
	5. Type of road	Public, Logging, and Snig track
	6. Geometry	Insloped, Outsloped, Crowned
	7. Road location	X, Y, and Z
	8. Topographic position	Crest and Pit or Depression
	9. Evidence of erosion	Yes/No
Cut and Fill Batters (Cutslope and Fillslope)	1. Slope gradient	Degrees and/or percent
	2. Height	Metres
	3. Length	Metres
	4. Vegetation cover	Percent
	5. Evidence of slope failure	Yes/No
	6. Evidence of erosion	Yes/No
Road Drainage Structures • Table Drain (Ditch) • Drains • Culverts	1. Drain types	Table drain, mitre drains, culverts, cross drains and push outs
	2. Road Contributing Width (RCW)	Metres
	3. Road Contributing Length (RCL)	Metres
	4. Road Contributing Area (RCA)	Square Metres (m^2)
	5. Slope gradient	Degrees and/or percent
	6. Hillslope gradient	Degrees and/or percent
	7. Location	X, Y, and Z
	8. Location of installation	Right/Left
	9. Table drains, drains or culverts' channel dimensions	Metres
	10. Size (diameter) of culvert	Metres
	11. Characteristics at the inlet and outlets	Technical specifications, construction
	12. Evidence of erosion	Yes/No
	13. Water flow length	Metres
	14. Direction of drains and culverts	Degrees
	15. Evidence of discharging failure	Yes/No
	16. Technical and working conditions	Yes/No, blocked, open
	17. Road-to-stream distance	Metres
	18. Road-to-stream connectivity	Yes/No/Gully/Diffuse
Rill and Gully Erosion on the Road Surface or at the outlets of Road Drainage Structures	1. Location	X, Y, and Z
	2. Slope	Degrees and/or percent
	3. Road Contributing Width (RCW)	Metres
	4. Road Contributing Length (RCL)	Metres
	5. Road Contributing Area (RCA)	Square Metres (m^2)
	6. Dimensions	Metres
	7. Direction	Degrees
	8. Type of erosion	Rill/Gully/Channel formation

Road Surface

The road surface or travelway is one of the main parts of the forest road prism. In this study, 'road prism' refers to the cross-sectional configuration of a road that includes the travelway, cut and fill batters and table drains (see also section 2.3.5, Chapter 2). At each road segment, a number of physical phenomena were recorded. These data described the exact location of road line, condition and characteristics of the road surface, road geometry and evidence of erosion – rill and gully – on the surface of the roads (Table 4.4). An important parameter for the type of the geometry is the slope of the road perpendicular to the hillside, which is characterised as insloped, outsloped, or crowned.

During each survey session, each vehicle pass was also recorded. This was later used in conjunction with the ACT Forest road information to classify road use into three categories: no traffic, occasional, and very light.

Cut and Fill Batters

In terms of erosion and failure, cut and fill batters are important parts of the road prism in steep terrain. As explained in Chapter 2, section 2.3.6, the erosion rates and road prism failure are expected to be high – because of cutslope failure, slump and/or mass movement – during or for a few years after road construction. Generally, cut batters or cutslopes should be as steep as the soils and bedrock permit, without becoming unstable. Fill batters or fillslopes can be built at various angles, depending on the properties of the soils and the building techniques used (Weaver and Hagans, 1994). In the case study area, the erosion rates from cut and fill batters were low, as almost all roads were built more than 30 years ago and have become stable over time.

The variables recorded for cut and fill batters are listed in Table 4.4. These data describe the characteristics, height, slope gradient and vegetation cover on cut and fill batters. The cut batters are more likely to fail when the height and slope gradient values are high and the vegetation cover is low. Evidence of slope failure – slump or mass movement – and rill and gully erosion on the cut and fill batters was also recorded. Generally, slope failures and slumps block the roadside table drains and redirect the flow of the runoff onto the road surface from the table drains. This causes rill and gully erosion on the road surface.

Drainage Structures

Table drains, mitre drains, push-outs, culverts and cross-banks are the most common road drainage structures installed along the roads to drain road surface. Table drains or roadside ditches are important for controlling runoff and draining roadways. On insloped roads, ditches are important parts of the road prism in collecting the runoff from the road surface (Figure 4.1).

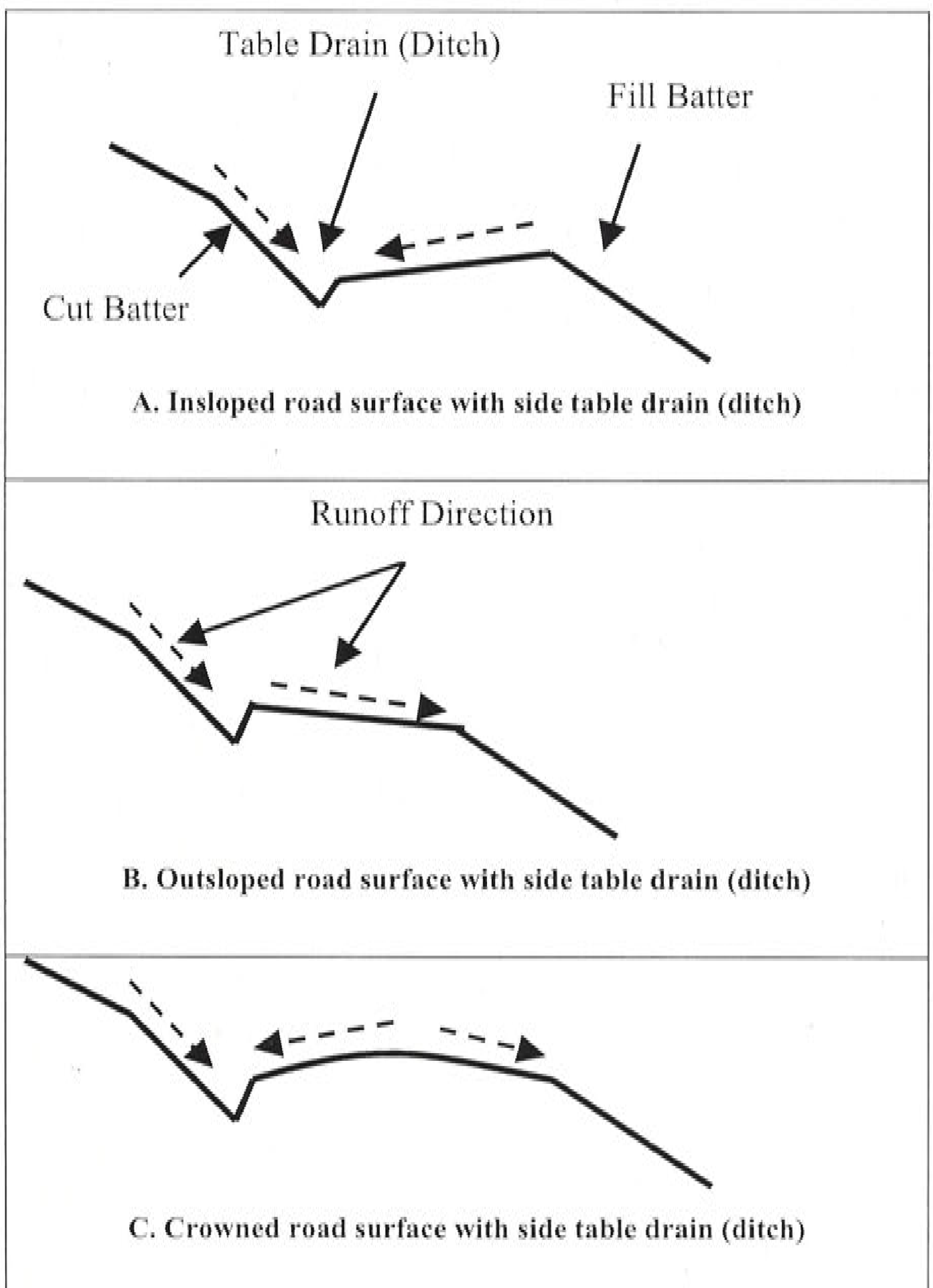


Figure 4.1. Schematic plan of cross sectional road prism with side table drain structure

Figure 4.1 shows three types of cross sectional road prism with ditch or roadside table drains. Table drains are one of the main parts of the roads that are built on steep terrain in order to collect runoff from the road surface and cutslopes. The drainage structure of an insloped road generally involves a side ditch and relief culvert. The road surface, being sloped inwards toward the cutslope, redirects the runoff it captures to the roadside table drain (Figure 4.1 A and C).

The mitre drain is one of the most common drainage structures used to discharge water from the surface of road and ditches. Generally, mitre drain systems are distributed in flat areas to control runoff from the surface of roads. In the steeper areas, managers and forest road planners prefer to design and use culverts for discharging and controlling runoff, in order to avoid surface erosion problems on the fill batter. Push-outs are also used to drain saddles, and topographic lows on ridgetop roads. Cross-banks are installed to drain skid tracks on steep ground and are to protect snig tracks against water erosion after the end of timber harvesting (Figures 4.2 and 4.3).

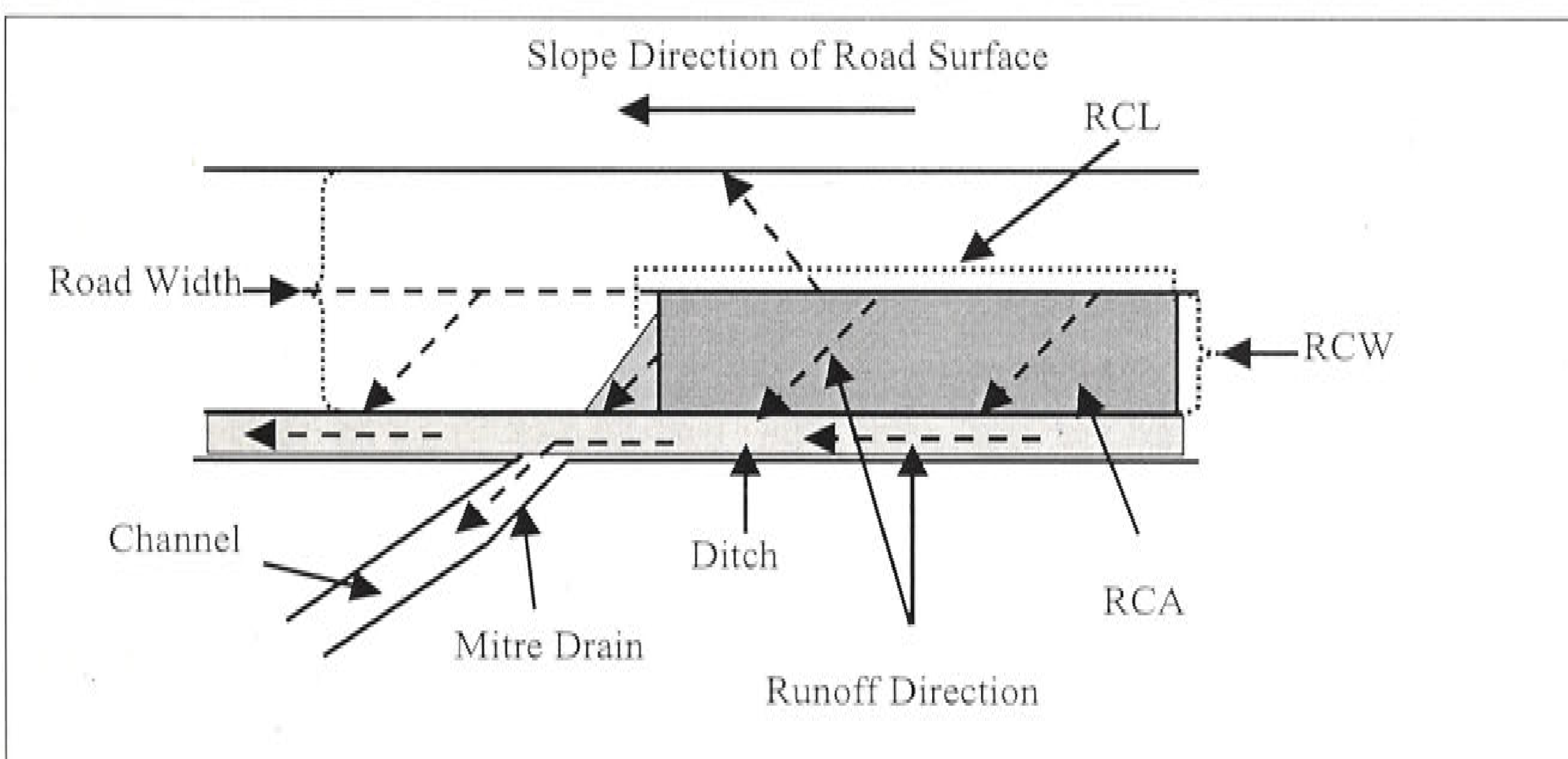


Figure 4.2. Schematic plan of a mitre drain structure

Figures 4.2 and 4.3 illustrate the mitre drain and push-out structures of forest roads in the study area. These types of drains are usually installed where forest roads are located on gentle slopes and flat areas. In these cases, the road does no usually have high cut batters. Road contributing area (RCA) is one of the most important parameters in road drainage management, especially when determining the correct position to install a drain. In both figures, the grided area illustrates RCA.

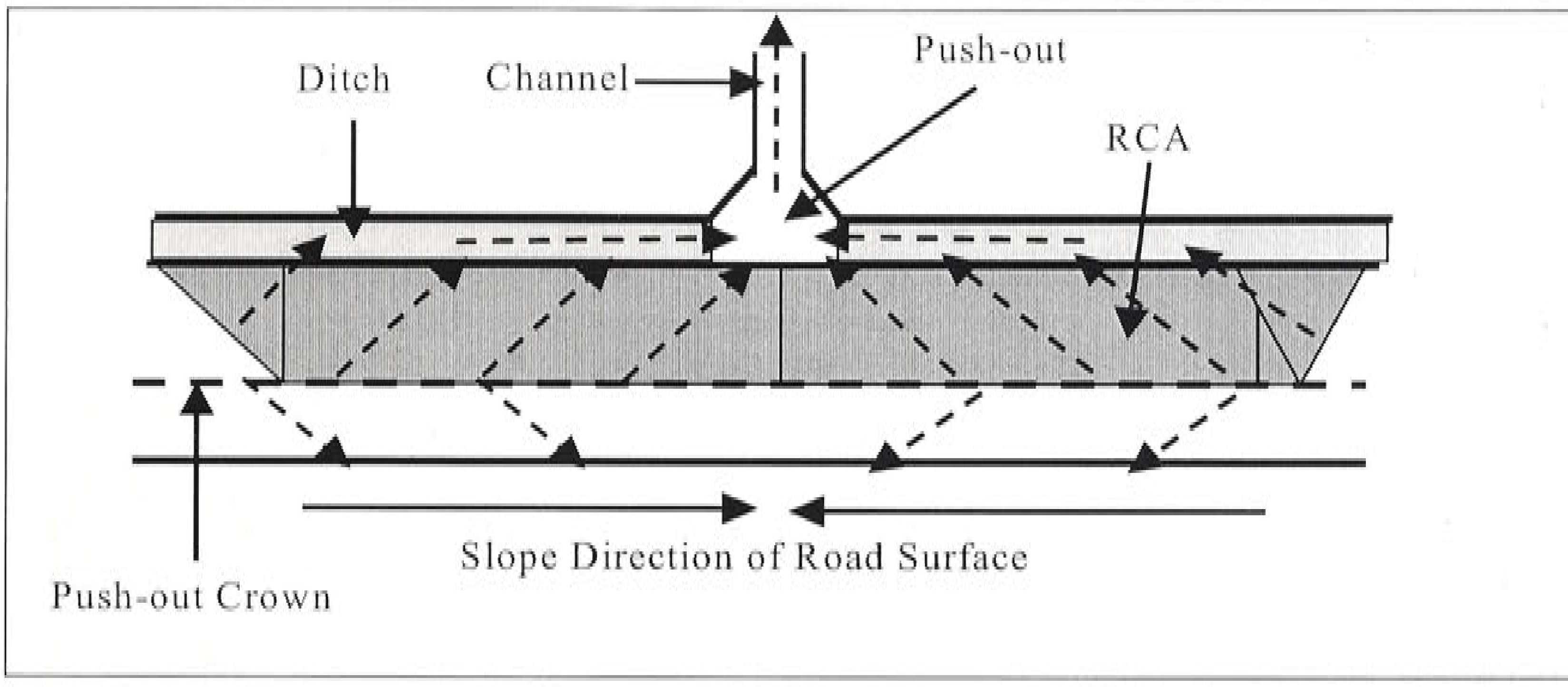


Figure 4.3. Schematic plan of a push-out drain structure

The correct magnitude of road contributing length (RCL) and width (RCW) of each drain is based on the geometry or shape of the road surface (insloped, outsloped, crowned), the distance between installed drainage structures and slope gradient of the road surface. These two variables, which together define the road contributing area (RCA), are important factors in forest road assessment and analysis in terms of calculating the possible runoff delivery to each drain and its capacity in discharging the runoff from road prism. However, physical features which might clearly suggest an undersized drain include channel width and drain or culvert-diameter-to-channel-width ratio. This last ratio integrates input and output capacities and can provide an important indicator in the field of exceedance probability (Furniss *et al.*, 1996). Additionally, evidence visible from field inspections of overflowing and redirection of runoff flow back from drain inlet onto the road surface was used to indicate partial or complete drain failure.

Two types of culvert drains are also used in the study area. 'Stream crossings' are built in streams and 'relief culverts' are installed to discharge the water from roadside table drains, mostly on the saddle points of the roads and where the cut batter of the road is high. Relief culverts divert water from the ditch, under the roadbed, and onto a stable slope below the road (Figure 4.4). Runoff from road surfaces and cut batters is concentrated in ditches and it is often impossible to discharge this by other drainage structures – mitre drains, push-outs and cross-banks – because of the roads' topographic position and the height of the cut and fill batters. However, bridges are installed on some of the stream crossing points where the volume of the discharged water is very high.

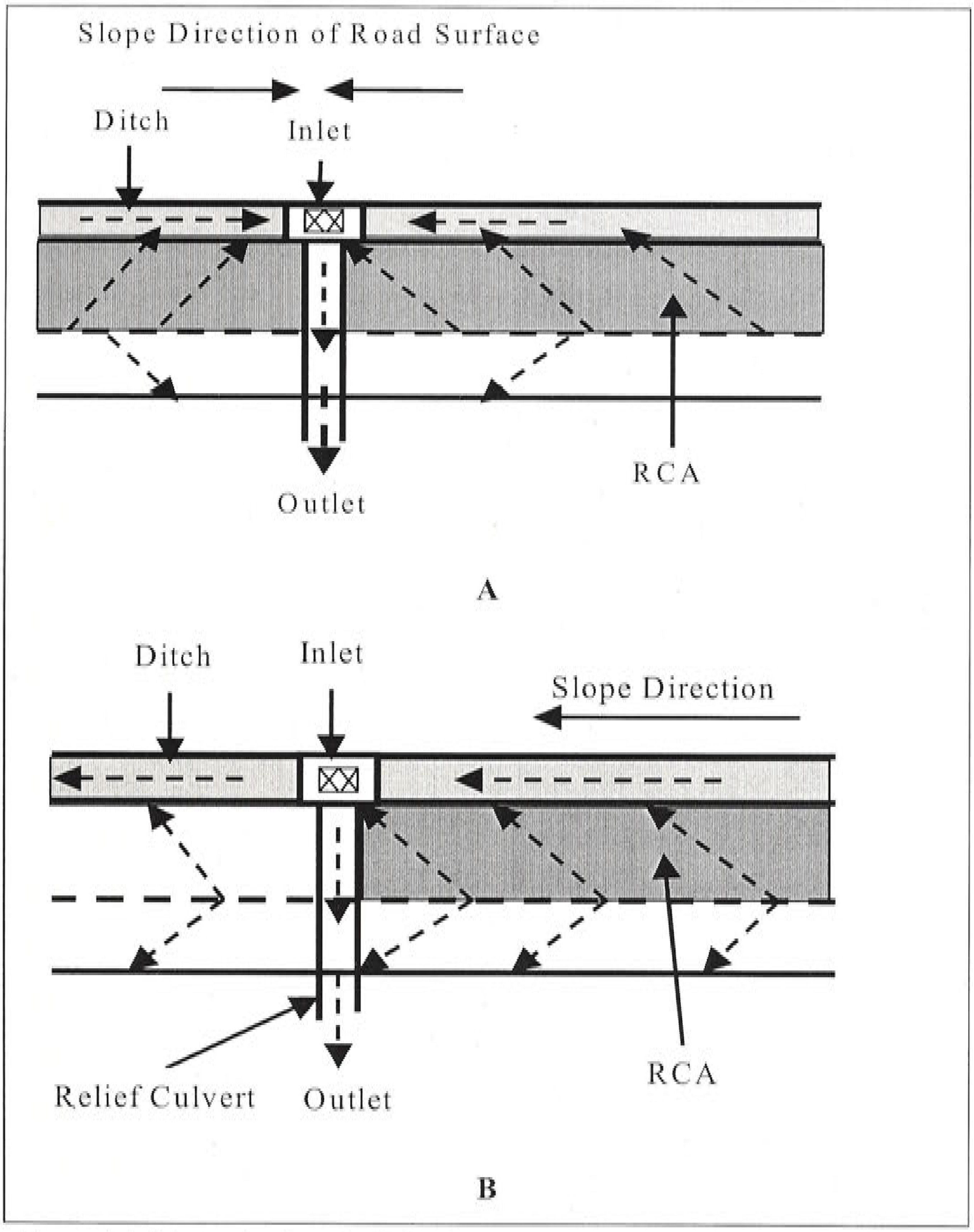


Figure 4.4. Schematic plan of relief culvert structures in the study area

Figure 4.4 illustrates the relief culvert structures. As shown in Figure 4.4 A, the direction of the runoff is toward the saddle point from both sides of the road and will be concentrated in the saddle point where the culvert is installed. In Figure 4.4 B, it is assumed that the road is located in steep terrain and the height of the cut batter will not permit the runoff to be managed with any other drain structure. In this situation, the water concentrated in the ditches must be broken down into smaller volumes by installing culverts and discharging the runoff onto the forest ground through fill batters. This process will reduce the RCA, resulting in a reduction of the erosive power of the runoff. As a result, the likelihood of the risk of ditch deformation and road surface erosion will be decreased.

In this thesis, all types of culverts and bridges are called 'culverts', and other drainage structures are called, 'drains' for the reason of simplicity. Both categories of drainage structures were aggregated in the statistical analyses.

Drainage Structures in the Case Study Area

Table Drains

Information related to the condition of roadside ditches is needed to correctly measure the RCL and RCW in the field. The RCA – the area of roadway that collects runoff for transferring into ditches – was then calculated by multiplying RCL and RCW. This information, and evidence of ditch failure, can be used to identify the factors influencing overflow runoff and sheet erosion on the surface of the roads. Data gathered from ditches were used for identifying the condition of the road surface and the inlets of drains, and the evidence of sediment production and delivery to the drainage structures. The variables recorded for table drains are listed in Table 4.4. These data described the conditions and characteristics of the table drains, channel formation and evidence of erosion. During the field survey it was also recorded whether the table drains were discharging water into a drain or culvert, and whether the table drains were well built in terms of technical considerations.

These technical considerations refer to the construction, dimensions, inside slope, correct location along the roadside, water discharge capacity and maintenance. The connection between roadside table drain and drainage structures is an important technical issue in table drain failure. Any lack of proper connection between table drain and road drainage structures can lead to failure, redirection of runoff onto the road surface, and possible surface erosion.

Drains

The Stromlo Forest road network is drained predominately by mitre drains. These form extensions of the table drain and redirect runoff onto the adjacent hillslope. The predominance of this type of drain reflects the high proportion of ridgetop roading (Croke and Mockler, 2001), but, mitre drains have also been installed on some roads located in the valley bottom and midslope.

The location at which the drainage structure is installed on the road is very important in terms of draining the road surface and discharging the runoff collected from the road prism. The distance between the drainage structures installed on the roads is also important to reduce the negative impacts on the road surface and outlet of drainage, by dispersing the volume of runoff to multiple smaller volumes. Consequently, the exact locations of all road drainage structures installed on the selected road segments were mapped in the field using the same process applied for mapping the road lines. The drain survey comprised the information and variables described in Table 4.4.

Any visible evidence of rill, gully and channel formation and sedimentation at the outlet of the drain was recorded. As the hydrologic distance between drainage structures and streams is important for road-to-stream connectivity assessment, flow pathway length – distance from the outlet of drain toward a stream – was measured in the field.

The ability of drains to discharge water is the most important characteristic of the road drainage structure in relation to the potentially adverse effects on the element at risk, stream water quality. One of the factors influencing the likelihood of overflow and road surface erosion is drainage failure consequent from the inadequate size or low discharge capacity of drains, and/or of them not being correctly located on the road. To investigate this issue, mitre drains were classified into six groups related to their capacity to discharge and control runoff from the surface of roads to the floor of the forest. These six groups and corresponding risk categories were:

1. The mitre is built well (in terms of technical specification) and is working very well;
2. The mitre is built well and is partly working;
3. The mitre is built well but is blocked;
4. The mitre is built badly but is working very well;
5. The mitre is built badly but is partly working;
6. The mitre is built badly and is also blocked.

Under this classification, the level of the risk associated with category 1 is the least – that is, negligible – and that with category 6 is the highest. This classification was also used during the analysis phase for evaluating risk associated with mitre drains.

Culverts

Culverts are other common drainage structures used in the Stromlo Forest road network. Generally, forest road culverts are used to drain the surface of a road to provide outlets for table drains and to allow streams or natural channels to pass through a roadway embankment (EPA, 1975). The location and technical specifications of culverts are very important for the control of runoff.

The variables recorded for culverts are listed in Table 4.4. These data describe the characteristics of the culverts, the exact location of the culvert along the road, with respect to surrounding topography, the situation at the inlet to discharge water, evidence of rill, gully and channel formation occurrence at the outlet and sedimentation at the inlet, outlet and channels, and also the length of flow pathways.

The type of inlet and outlet construction and the risk of a culvert failing to discharge water were assigned to four categories:

1. Inlet and outlet are built of concrete, and culvert condition is good;
2. Inlet and outlet are built of stone, and culvert condition is fair;
3. Inlet and outlet are built of wood, and culvert condition is poor;
4. Inlet and outlet have no construction of the above types.

Categories 1 and 2 have negligible and very low risk of failure in discharging water, respectively, and categories 3 and 4 have a medium to high risk of failure in discharging water depending on other factors like the size of the culvert. The construction of inlets and outlets is extremely important for the culverts to work. Therefore, they were classified as open, partly working, or blocked.

Any evidence of road-to-stream connectivity was also recorded in the field for all types of drainage structures. Each outlet of the drainage structure or road segment was classified into one of three categories based on whether its outlet delivered water: (1) directly to an adjacent stream (that is, stream-crossing and/or diffuse connection); (2) into a gully incised below the drainage outlet (that is, gully connection); and (3) onto a hillslope where the water re-infiltrated the soil (that is, no connection). Road segments in category 1 are mostly located in the valley bottoms and the road-to-stream connection is mostly a diffuse linkage because of the short distance between roads and streams. Road segments assigned to category 2 were mostly located in midslope, and there was evidence of gully erosion and formation of a canalised flow path for a certain length (at least 10 metres) below the outlet of a drainage structure. Category 3 road segments were located mostly on ridgetops or far away from the streams, and there was no evidence of erosion or road-to-stream connection. These field data were used to verify the road-to-stream connectivity predicted by the models (see also section 4.6.2 and Chapter 7).

Mapping Rill and Gully Location and Recording Their Physical Characteristics

One of the most important parts of the forest road analysis and the field survey was intended to identify those areas of the forest roads that are problematic in terms of soil erosion. The location of the rills or gullies on the surface of the roads and at the outlets of the drainage structures and their physical characteristics are key factors for spatial assessment and analysis of the problem areas.

The exact locations of rills and gullies on the road surface, and at the outlet of the road drainage structures, were mapped using the same process applied for mapping drains and culverts. Channel formation and evidence of sedimentation at the inlets and outlets of the drains and culverts were also recorded. Data collected for each rill and gully on the surface of the roads or at the outlets of the drainage structures are listed in Table 4.4. These data describe the dimensions of the rill and gully erosion, RCW, RCL and RCA related to each rill or gully point, and information related to the possible connection between the erosion and the failure of table drain and the drainage structure (blockage, non-functionality, technical problems (for example, construction and poor positioning) and cutslope).

Moreover, all factors which could be seen to have influenced the occurrence of rills or gullies on the surface of the road – including evidence of ruts on the roads, possible linkages between the erosion point to upslope runoff delivery, and other visible related information – were also recorded. All of the data and information collected were attached to the road network map as a table of attributes. This database was used to create an integrated data set for the Stromlo Forest road network (as discussed in section 4.4).

4.3.4 Partitioning the Field Data into 'Development' and 'Validation' Data Sets

As noted previously, the most widely used evaluation technique in data analysis is partitioning sample data into development and validation data sets (Small and Edelstein, 1997; Hand *et al.*, 2001). A model is built from a development set and its performance is subsequently tested on a validation set. The simplest approach to partitioning a data set into development and validation sets is by random sampling. In simple random sampling, every observation in the main data set – data collected from the field survey – has an equal probability of being selected for the two partitioned components of data set.

As explained in Table 4.3, because of the lack of prior information about the population, information from the field survey was used to estimate the development data set size. To determine the required size of a sample, the standard deviation of the population must be known. It is rare for a researcher to know the exact standard deviation of the population. Typically, the standard deviation of the population is estimated from the results of a previous survey, a pilot study, secondary data, and/or the judgment of the researcher. In this study, the standard deviation was estimated from the field survey. Maximum acceptable difference and desired confidence level are the other parameters necessary for estimating the appropriate sample numbers. The former is the maximum difference by which the sample mean can deviate from the true population mean before calling the difference significant (Patten, 2002; Pavkov and Pierce, 2003; Bass, 2005). The confidence level is a level of certainty that the sample mean does not differ from the true population mean by more than the maximum acceptable difference. Typically, researchers use a 95% confidence level.

Formulas 4.1, 4.2 and 4.3 can be used to estimate the size of the development set from the field survey population (Patten, 2002; Israel, 2003). Cochran (1977), Evans *et al.* (2000) and Rainbow Research (2005) developed a formula (Formula 4.1) for large populations, representing a sample size for proportions:

$$n_0 = \frac{Z^2 pq}{e^2} \tag{4.1}$$

where n_0 is the sample size, Z is the abscissa of the normal curve that cuts off an area at the tails, e is the desired level of precision, p is the estimated proportion of an attribute that is present in the population, and q is 1 - p. The value for Z is found in statistical tables which contain the area under the normal curve. When there is a large population and the variability in the proportion is not known, the estimated proportion can be calculated by assuming as a maximum variability or p=0.5. In this study, the desired level of confidence and precision (acceptable margin of error) were set at 95% and ±5%, respectively. The sample size (n_0) can be adjusted using 'The Finite Population Correction' (Cochran, 1977; Steel and Fay, 1995; Israel, 2003) (Formula 4.2):

$$n = \frac{n_0}{1 + \frac{(n_0 - 1)}{\mathrm{N}}} \tag{4.2}$$

where n is the sample size, n_0 is the sample size from Formula 4.1 and N is the population size. A simplified formula has been developed by Yamane (1967) to calculate sample sizes. A 95% confidence level and P = 0.5 can be assumed for this formula (Formula 4.3):

$$n = \frac{N}{1+(N * e^2)} \qquad (4.3)$$

where n is the sample size, N is the population size and e is the precision (acceptable error).

The Z value for a 95% confidence level corresponds to $\alpha = 0.05$, and the corresponding critical value in normal distribution tables is therefore $Z_{\alpha/2} = 1.96$, thus,

$$n_0 = \frac{(1.96)^2(0.5 * 0.5)}{(0.05)^2} = 385$$

The sample size, after adjustment applying the finite population correction using Formula 4.2, is estimated as:

$$n = \frac{385}{1+\frac{(385-1)}{685}} = 247$$

The estimated sample size, using the simplified Formula 4.3 is:

$$n = \frac{685}{1+(685 * (0.05)^2)} = 253$$

Therefore, the acceptable sample size for development data set for this study is around 250 (from 247 to 253). The development sample for the field survey was selected randomly from the population using the random sampling option of the statistical software SPSS and STATISTICA; the number generated by those packages was 254.

The population sample of 685 observations was therefore partitioned with a development data set of 254 observations, and a validation data set of 431 observations. Table 4.5 summarises the summary of the descriptive statistics of key variables of the whole population and the development and validation data sets. The comparison of the mean, standard deviation, standard error and variance of most variables shows that the development set is a good sample of the population.

Table 4.5. Descriptive statistics of key variables from the field survey population, development, and validation data sets

Variable	Data sets	N	Range	Min	Max	Mean	Std. Error	Std. Deviation	Variance
Contributing Area	Field survey	685	417	9	426	66.30	2.35	61.38	3767.64
	Development	254	403.5	9	412.5	66.29	3.59	57.24	3275.97
	Validation	431	416	10	426	66.29	3.07	63.76	4065.69
Hillslope Gradient	Field survey	685	54	3	57	16.73	.29	7.49	56.16
	Development	254	53	3	56	17.22	.53	8.42	70.96
	Validation	431	51	1	52	16.42	.33	6.9	47.55
Elevation	Field survey	685	257	508	765	591.01	1.66	43.49	1891.6
	Development	254	222	510	732	592.00	2.69	42.88	1838.63
	Validation	431	257	508	765	590.43	2.11	43.89	1926.24
CTI	Field survey	685	12.95	5	17.95	7.99	.07	1.77	3.13
	Development	254	9	5	18	8.1	.11	1.76	3.08
	Validation	431	12	5	17	7.92	.09	1.78	3.16
SPI	Field survey	685	629755	2	629757	8063.67	1561.46	40867.3	1670139460.85
	Development	254	587168	44	587212	8457.6	2716.06	43286.83	1873749797.09
	Validation	431	629755	2	629757	7831.51	1898.88	39421.81	1554079174.58
Slope	Field survey	685	41	1	42	10.78	.19	4.91	24.07
	Development	254	41	1	42	10.56	.32	5.09	25.93
	Validation	431	41	1	42	10.74	.23	4.8	23.03
Distance	Field survey	685	1615	2	1617	297.25	13.19	345.25	119195.5
	Development	254	1615	2	1617	302.11	22.56	359.52	129255.6
	Validation	431	1615	2	1617	294.38	16.23	336.94	113531.5
USCA	Field survey	685	158173	20	158193	1492.44	392.80	10280.47	105688098.17
	Development	254	149369	20	149416	1632.27	663.52	10575.8	111832368.89
	Validation	431	158173	20	158193	1410.03	487.19	10114.37	102300410.38
RCL	Field survey	685	348	7	355	45.85	1.37	35.76	1278.79
	Development	254	267	8	275	45.59	2.09	33.28	1107.85
	Validation	431	348	7	355	46.01	1.79	37.18	1382.27
RCW	Field survey	685	3	0	4	1.37	.02	.567	.321
	Development	254	3.1	.40	3.50	1.41	.037	.587	.345
	Validation	431	3	0	4	1.34	.03	.554	.306

4.4 Terrain Modelling and Analysis

4.4.1 Obtaining Topographic and Digital Maps

The digital maps of the study area, including the forest road network and details of the topography, were obtained from ACT Forests. Satellite imagery of the ACT and adjacent southern NSW regions taken in 2000, 2002 and 2003 (pre- and post-bushfire) were provided by NSW National Parks and Wildlife Service (NPWS) and CSIRO Forestry and Forest Products. Topographic maps and images were used for creating DEM at 20 m and 40 m resolutions for the pre-pilot study and testing DGPS data collection. Subsequently, a DEM, initially at 20 m resolution, was obtained from CRES, ANU (CRES, 2003), and used for the main study. Other maps and GIS layers essential for the study were created using DTM processes.

4.4.2 Conducting DTM, Topographic and Terrain Analysis

Preparation of the Maps and DEM

Preparation of maps and GIS layers is the first step of topographic and terrain analysis. It includes geographic projection, clipping, joining and/or separating the targeted area from the original maps, comparing the satellite image and DEM with topographic maps, and checking the error of the DEM using GIS techniques.

Application in this Case Study

The GIS layers were projected using the projection coordinate system of Australia known as the 'Australian Map Grid' or 'Geocentric Datum of Australia' (GDA) and the Universal Transverse Mercator (UTM) System (GDA_1994_UTM_Zone_55s) and Geographic

Coordinate System (GCS) (GCS_GDA_1994) for the study area, using ArcGIS (versions 8.3 and 9) and ArcView version 3.2a. The Stromlo Forest compartments and adjacent area were then separated from the original maps and DEM by overlaying the road network as a mask layer using IDRISI and ArcGIS. These layers were later used to define the basin area, associated watersheds and sub-watersheds of the study area for hydrologic modelling.

Errors in the DEM and Relationship to Errors in Using DGPS

A DEM is a computer representation of the earth's surface that provides a base data set from which topographic parameters can be digitally generated (Wechsler, 2003). All DEMs have limitations according to their production methods and the data from which they were derived. According to Burrough (1986) and Wise (1988), the sources of possible error in DEM data sets include:

1. Data errors due to the age of data;
2. Incomplete density of observations or results of spatial sampling;
3. Measurement errors in relation to the positional inaccuracy, data entry faults or observer bias;
4. Processing errors, including numerical errors in the computer, interpolation errors or classification and generalization problems.

Errors in the use of DGPS in forest-related work are related principally to: (1) the time of data gathering, reflecting the availability of satellites for the particular area zone; (2) the density of any tree canopy, and; (3) systematic or technical biases due to the instruments or data collector. Most of these errors can be controlled or avoided.

As described in section 4.2, an Ashtech (Magellan Corporation, 1998) DGPS was used to collect data from the field. The use of this DGPS allowed a high level of mapping accuracy. The Ashtech DGPS system provides an estimate of the accuracy of each data collection location; in the case of this study, approximately 97% of the sites were accurately located within about 20 cm. This also suggests that there were no systematic or technical biases. Given that data collection took place after the overstorey vegetation had been burnt in the 2003 bushfire, there were no inaccuracies due to canopy cover.

Application in this Case Study

A DEM of 40 m resolution was built by the author for the study area in 2002 using a topographic map of the area. The accuracy of this DEM was tested using a limited number of sample points that represented the accurate elevation value, as there were doubts about the level of its accuracy and error margins. Therefore, the existing DEM was used only for a pre-pilot study at the beginning of the work and for providing material for a paper, included as Appendix F. Subsequently a DEM of the ACT with a resolution of 20m, belonging to the NSW Government, was provided from CRES, ANU, where it had been evaluated and its accuracy was tested. The DEM has been built using original source data with a 20 m grid resolution. This can be assumed to have negligible error. The DEM 'standard elevation error' depends on the local slope and grid resolution, which is formulated as:

$$SE = slope * h/sqrt(12) \tag{4.4}$$

where

SE = error in metres;

and h = the grid spacing (M. Hutchinson, pers. comm., 12 May 2005).

Based on this formula, the error is less than 0.3 m for a 5% slope and less than 1.2 m for a 20% slope. As the average slope of the study area is about 10%, the average error is <0.6 m, and is effectively negligible.

DTM and TA

Digital Terrain Modelling (DTM) is a powerful tool in GIS analysis and visualization. It is defined as the study of ground-surface relief and pattern by numerical methods, and has become integral to hydrology, topographic and geo-hazard assessment (Pike, 1995). Digital terrain layers can be stored in a GIS in several ways: as a set of contour vectors; as an irregularly spaced set of points connected as triangles known as a Triangular Irregular Network (TIN), and a regular grid of spot heights known as a Digital Elevation Model, or DEM (see also Chapter 2). The computer processing of squared-grid arrays of terrain heights (DEM) has revolutionized the discipline's two chief functions of topographic analysis and display (Moore *et al.*, 1991; Pike, 1995). GIS technology further enables terrain-modelling results to be combined with non-topographic data. The resolution at which elevation data points are sampled to build a DEM is important in determining the usefulness of the resulting DTM.

Application in this Case Study

As stated above, a DEM of the study area with an acceptable resolution, at 20 m, and accuracy (CRES, 2003) was used for topographic analysis. All necessary terrain attribute layers for the study were built up or derived from the DEM, using relief analysis and approaches derived from Moore *et al.* (1991), Gallant and Wilson (2000), Pallaris (1999, 2000), and Reuter (2003). The relief analysis was applied using ArcGIS analysis processes, including second order finite differences and fitting a bivariate interpolation function. All primary terrain attributes of the study area – slope, aspect, curvatures (profile, plan, tangential and total), flow direction and flow accumulation – were calculated from directional derivatives of a topographic surface using the DEM (see also Chapter 2). The 'secondary relief parameters' – Topographic Wetness Index (TWI) (also referred to as Compound Topographic Index (CTI)), Stream Power Index (SPI), Upslope Contributing Area (USCA or SCA) and Sediment Capacity Index (SCI) – were then computed. Other terrain attributes – slope length and drainage area – were also calculated using relief analysis and the formula explained in section 2.4, Chapter 2. Slope and slope length were later used to calculate variables, such as slope (S) and slope length (LS) factors, used in soil loss assessment in RUSLE models. The details and results of these analyses are explained in Chapters 5 and 6.

Landform Classification and Slope Position Analysis

Landform and slope classification are necessary processes for gathering and managing natural resources data. They provide the foundation data for natural management and planning. According to Hammond (1964), Speight (1974, 1990), McNab (1989, 1991, 1993) and MacMillan *et al.* (2000), landform classification can be defined as a quantitative procedure which uses values of slope gradient, relative relief (differences between maximum and minimum elevation), and profile type to define different landforms. Landform classification allows calculation of the percentage of the area where the ground is flat or gentle, the relative relief, and also the relative proportion of flat or gently sloping terrain. Topographic position analysis allows estimation of position of the location and extent of crest defined as an area high in the landscape, having positive plan and/or profile curvature; of a depression defined as an area low in the landscape, having negative plan and/or profile curvature; of a simple slope, lower, mid-slope and upper slope; and of a rigetop defined as a compound element containing at least 2 opposing planar slopes meeting at a very narrow crest (Speight, 1990; McNab, 1991, 1993; MacMillan et al., 2000).

Both landform and slope position analysis can be applied using GIS-based applications and modelling. The final result of applying the model will be a coverage polygon map, from which the percentage of the area for each category can be calculated.

Application in this Case Study

In this study, a landform classification was carried out using a concavity/convexity index calculated following concepts introduced by McNab (1991, 1993), Bolstad (1998) and Jeffrey (2002). The landform and topographic position analyses were carried out using a GIS-based program described by Hatfield (2003). First, general terrain attributes were derived from DEM using DTM. Some of these terrain attributes – slope, aspect, flow direction, flow accumulation and curvature layers – were then used for landform classification in conjunction with DEM. The landforms were classified in 10 classes, from very flat to cliffs (see Chapter 7 for details).

Topographic position is generally classified using the distance of the road from an adjacent ridgetop to the nearest high – fourth or fifth – order stream. Wemple *et al.* (1996) defined three hillslope positions layers used to develop strata for field sampling: valley bottoms were the area within a 100-m buffer around the fourth- and fifth-order streams; ridgetops were the area within a 100-m buffer around the boundary of sub-basins of more than 100 hectares; and midslopes were the remaining area. As described in section 4.3.2, the slope positions of the study area and its forest road network were calculated and classified into three categories: ridgetop, midslope, and valley bottom using the processes were developed by Wemple (2001), Hatfield (2003) and Takken *et al.* (2005). An Arc Macro Language (AML) from the USDA, originally written by Hatfield (2003), was adapted for the study. Hatfield (2003) used a grid of elevation values (DEM) to create a grid of slope position. He defined the slope position of a pixel as its relative position between the nearest valley floor and the ridge top. The slope position of each pixel is then calculated by dividing its relative elevation value by the differences between valley bottom and ridgetop and expressing this as a percent (see formula 4.5).

$$SP = INT\,[(E_p - E_v) / (E_r - E_v) * (100)] \tag{4.5}$$

where SP is slope position of a pixel, INT is integer, E_p is the elevation value of pixel, E_v is the relative elevation value of valley bottom and E_r is the relative elevation value of ridgetop.

Hatfield (2003) used formula 4.5 to represent slope position as a ratio, ranging from 0 (valley floor) to 100 (ridgetop). The slope position value of all pixels will therefore be assigned from 0 to 100%.

A DEM layer (20 m resolution) and forest road network layer of the study area were used as inputs for running the model in ArcInfo. The output of the model is a grid layer with values ranging from 0 (valley bottoms) to 100 (ridgetops). Slope position values were derived by interpolation for the remaining areas. To create the final slope position map, three different thresholds were defined to assign slope position boundaries: $\leq$ 20% for the valley bottom, >20% and $\leq$80% for mid-slope, and >80% for ridgetop zones.

Stability Index (SI) assessment was also carried out for the study area and the forest road network. The SI was calculated and mapped using an ArcView GIS-based model called 'SINMA' (Stability Index Mapping) model developed by Pack *et al.* (1998). SI is generally calculated in order to address mass wasting or landslide hazards. However, the SI analysis can also be used to indicate the segments of roads that are more likely to have sheet erosion (rill and gully) due to table drains becoming blocked by cutslope failure (that is, slump). The SI results were then compared with the field data collected from the road cutslope.

4.5 Forest Road Analysis

This section describes the processes used to analyse the roads, develop and verify the forest road maps, and assemble road-related spatial and non-spatial data. One of the main objectives of the forest road analysis is to create and develop a comprehensive road data set for easy storage, retrieval, analysis and updating of information, using both spatial and non-spatial variables.

4.5.1 Forest Road Network and Slope Position Analysis

As explained in section 4.3.3, the forest road network map provided from ACT Forests was checked, updated and verified by ground investigation. The location of sample road lines was recorded using DGPS, and transferred into GIS where it was stored as a vector layer. This layer was then compared with the digitised road layer, and the overlay application proved acceptable in terms of road mapping accuracy.

Calculation of road slope-position has been used in forest engineering research for the past 10 years, particularly for selecting road segments for detailed survey and examining road to stream connectivity (Montgomery, 1994; Wemple *et al.*, 1996; Croke and Mockler, 2001; Wemple *et al.*, 2001; Hatfield, 2003; Takken *et al.*, 2005). For these purposes, it is important to know the exact position of a forest road layout on the ground, and how far the road is physically located from the stream.

As explained in sections 4.3.2 and 4.4.2, the road slope position analysis for the study area was carried out using the same processes and methodology used for landform and topographic position analyses. The final outcome of the model is a coverage polygon describing three different zones – valley bottom, mid-slope and ridgetop – based on the defined thresholds. Subsequently, the road layer was intersected with the slope position zones, and the length and percentage of the road network in each zone were calculated.

Extracting Relevant Terrain Attributes Values from the Terrain Layers and Assembling Spatial Data

All terrain attribute data relevant to the recorded drainage structures were extracted from terrain layers using GIS techniques (that is, spatial overlaying, combining and intersecting). All vector (coverage and shape) layers were then displayed in the ArcMap or ArcView environment and the necessary analysis conducted, using spatial analysis or intersection application, to extract the data related to each point or line.

Raster analysis – including overlay, combine and grid commands of ArcInfo, IDRISI and ERDAS IMAGINE – and an Arc Macro Language (AML) called 'gridspot70.aml' (ESRI, 1998) – were used to extract the spatial data from the grid layers.

Creating Single Integrated Data Set for Roads and Drainage Structures

A comprehensive data set was created for both forest road and road drainage structures by integrating both field-collected data and relevant extracted terrain data, in order to easily store, manage, retrieve, analyse and update information. All extracted terrain data – slope, aspect, CTI, SPI, upslope contributing area, elevation, curvatures, slope length, flow lines or flow pathway and slope position – were assembled and integrated into a table of attributes for drain and culvert layers. Most of these data were joined spatially and directly from terrain layers using GIS spatial analysis. However, some of non-numerical data were added to the data sets using other GIS and database management methods and techniques (for example, intersection, join and merge). These integrated data sets were used in subsequent analyses.

4.6 Hydrological Analysis

Watershed or stream delineation is one of the most fundamental processes in hydrologic analyses. In this study, a watershed refers to a region draining into a stream or river system.

A stream also refers to a watercourse where water may flow at least 2 months of the year (FAO, 1999). Streams are generally identified by their 'order', which is a measure of the relative size of streams identified by a numerical code sequence (Strahler, 1964; Allan, 1995). A first order stream is the smallest size of stream, originating with a spring or through drainage after precipitation. A second order stream is formed when two first order streams flow together, and a third order stream is formed when two second order streams meet. A fourth order stream is formed when two third order streams meet, and the fifth order stream is formed when fourth order streams meet.

Conducting Stream and Watershed Delineations for the Case Study Area

The principal aim of this study, as articulated in the hypothesis, was to ascertain whether the road-derived runoff is likely to deposit sediment into an adjacent stream. Predicting the extent of the overland flow and runoff from the surface of the road, and the possibility of flow with sediment reaching streams, are essential parts of hydrologic analysis. The DEM of the study area was used for this analysis. ArcGIS, ArcView and TauDEM (Tarboton, 2004) extensions were used to delineate the watershed. The stream network, basins, watershed and sub-watersheds were created and characterised by implementing the delineation.

4.6.1 Model the Flow Pathways Length (Predicting Road-to-Stream Hydrologic Distance) Using GIS-Based Models

The factors influencing the likelihood of overflow and road-to-stream connectivity are the location of drains, the road contribution area, the slope gradient, the distance between roads and streams, drainage failure and the size or capacity of drains. All of these variables were measured in the field or extracted from the DEM.

As mentioned previously in Chapter 1, prediction of the hydrologic distance (flow pathway) between the outlets of the drains to the nearest watercourse using GIS modelling was one of the objectives of the study. It is used to define road-to-stream connectivity.

Therefore, this distance was measured in the field as the basis for comparing and validating the different prediction models. As measuring the distance between the outlets road of drainage structures and streams is difficult, time-consuming and expensive work, a sample of the drains was selected at random. The sampling intensity was about 1/3, based on the sampling fraction explained in section 4.3.2. For each road segment, the first sample drain was randomly selected, and every third drain was then chosen for measurement of distance to stream. In total, the hydrological distances from 250 drainage structures were measured. The measurement of flow pathways was based on the topography, slope direction, depression and any other evidence that showed where water would have flowed from the outlet to the stream. Visible evidence of the flow path from the outlet toward the stream facilitated the measurement of the actual flow distance on the ground. The distance from the outlet of each drain to the nearest watercourse was measured along the direction of the actual flow pathway. As in other field surveys, a DGPS, a metric survey tape and clinometer with accuracy to $\pm$ 0.5° were used to measure the actual road drainage-to-stream path lengths and slope.

The hydrologic distance between roads at the outlets of the drainage structures and streams was then predicted. The hydrologic distance was also predicted using five GIS-based models, including ArcInfo *NEAR* method, *FLOWLINES* and FLOWPATH programs, MapWin and TauDEM extension for ArcGIS. The predicted distance of flow length was then compared with the field-measured distance to find the best estimated distance or model. These models are described in Chapter 7.

4.6.2 Water Quality and Forest Road-to-Stream Connectivity

Over the last two decades, many researchers (for example, Amaranthus *et al.*, 1985; Brown, 1989; Novotny and Chesters, 1989; Lacey, 1993; Wemple *et al.*, 1996; Croke *et al.*, 1997; Croke and Mockler, 2001; McRobert and Sheridan 2001; Ziegler *et al.*, 2002) have focused on runoff, water flow paths and the connectivity between roads and streams as the key attributes of determining the impacts of forest roads on water quality.

Generally, runoff is generated when soil is saturated. Soil water content and the surface saturation zone can be identified using a Compound Topographic Index (CTI). "Runoff from saturation zones is a threshold process and areas producing saturation overland flow can be identified using threshold wetness index" (Moore *et al.*, 1993:17). Using the wetness index as an indicator of the spatial distribution of water content and soil water drainage has not been totally successful, however, because of the limitations of these two measures (Jones, 1987). However, Moore *et al.* (1988) argued that there is a strong correlation between the distribution of wetness indices and the distribution of water content in a small catchment. Because of the nature of the wetness indices by which the soil water content and saturated zones can be identified, the relationship between wetness indices and other attributes is predictable.

The topographic position of road attributes is very important to hydrological assessment of the road prism. Moore *et al.* (1993) stated that the relative magnitudes of many hydrological, geomorphologic, and biological processes operating in natural landscapes are sensitive to topographic position.

The connectivity between the source of sediment (in this case, the road) and watercourses has been recognised as a main factor in water quality impacts by many researchers. Novotny and Chesters (1989) claimed that most impacts on water quality depend on the runoff and soil erosion sources and the connectivity between sediment sources and the runoff delivery to the stream. Road surfaces are a significant source of sediment delivery to streams via water flow paths from drainage outlets, especially when heavy storms occur (Brown, 1989).

Wemple *et al.* (1996) separated a catchment into three areas for the purpose of studying water quality: ridge top, mid-valley and streamside. Montgomery (1994) identified the drainage outlets and discharge points at three different locations: (1) where flow was directed from the road surface either onto a hillside or into a channel; (2) where table drains or roadside ditches delivered flow to culverts, and (3) where road surface drainage ran repeatedly over road margins and onto hillsides.

Croke and Mockler (2001) argued that contributing road length and the gradient of the discharge hillslope are two important factors for planning and rehabilitation of forest roads in order to control water quality impacts. They used a linear discriminant analysis for analysing and evaluating these factors in order to separate channelled and non-channelled flow pathways within a catchment.

Moore and Burch (1986) developed the unit stream power theory of sheet and rill flow in order to predict the sediment transport capacity. They also argued that "the application of unit stream power theory to soil erosion would be even more successful than its usual application to river studies of sediment transport" (Moore and Burch, 1986:1351). The effects of slope, catchment size, morphology and shape of rill, and water and sediment discharge from the rill have been examined for sediment transport from rill flow (Mosley, 1976, 1981, 1982). Mosley also measured the morphological characteristics of each rill-initial surface slope, rill catchment area and channel slope. Moore and Burch (1986) stated that Mosley's rill data and results from his study are suitable for testing the application of unit stream power theory in order to predict the sediment transport capacity of rill flow. Note that there is a strong relationship between concentration of water flow (convergence) and divergence of surface water flow with rill formation and sheet erosion, respectively. Moore and Burch (1986:1354) argued that "convergence or divergence of a flow surface affects the number of rills formed on the surface and the catchment area of each rill".

Moore *et al.* (1988:1098) defined ephemeral gullies as "small channels that are formed in the same locations, usually in natural depressions or waterways, during erosion events". Gullies occur when the flow concentrations wash the surface soil and carry the sediment away, and in consequence channel formation begins. Soil will be detached from the bed and walls of the channel by concentrated flow (Moore *et al.*, 1988). This process can create substantial sediment that will be delivered directly or indirectly to the stream by water flow.

Application in this Case Study

In this study, road-to-stream connectivity was tested using the logistic regression and threshold curve approach introduced by Croke and Mockler (2001). They used an equation

(equation 4.6) for assessing and classifying the presence and absence of the channel or gullied pathways at the road drainage outlet around the threshold RCL (L_t) for a range of discharge hillslope gradients (θ):

$$L = m / \sin(\theta) \tag{4.6}$$

where L is the contributing length of the road serviced by a drain, m is cumulative frequency curves of road contributing length (RCL), and θ is the hillslope gradient at the outlet of drain (drain discharge point). Croke and Mockler (2001) classified a drain as linked when $L > L_t$, and as unlinked when $L < L_t$. The partially-linked drain points were classified as linked drains based on the field observation for the purpose of analysis. They also predicted the characteristic or threshold road length and area by the following formulae:

$$RCL = 25m / \sin(\theta) \tag{4.7}$$

$$RCA = 70m^2 / \sin(\theta) \tag{4.8}$$

RCL, RCA, the hydrological distance between roads and streams and hillslope gradient at the outlet of drains, were used in this study as inputs for the road-to-stream connectivity assessment. Before this assessment, slope position and landform analyses were applied in order to identify the road position in the catchment and classify the roads for study. Watershed delineation is necessary for predicting the distance and connectivity between roads and streams. All processes, procedures and results of this assessment are presented and discussed in Chapter 7.

The type of road-to-stream connectivity was classified using field observation and the results predicted from the analysis. Diffuse overland flow connectivity between outlet of the drains and streams was predicted using both field observation and the approaches described by Hairsine *et al.* (2002). Hairsine *et al.* (2002) introduced a model called 'vbt5', the volume to breakthrough for a 5 m length of the hillslope. The volume to breakthrough is the volume of runoff that enters an area before a discharge is observed at the downslope boundary of that area or at the outlet of cross-bank and drains (see also Chapter 7). Also, volume (vbt5) "is a combination of water lost to overland flow through infiltration, water stored above ground in depression storage and water in transit between the upper and lower boundary of the area" (Hairsine *et al.*, 2002:2314). For this study, a steady-state infiltration rate of 11.7 mm/hr was used, based on the correspondence to the mean value during rainfall simulations on unsealed forest roads reported by Croke *et al.* (forthcoming). They described the overland flow by equation 4.9:

$$L_{pred} = 5\ (V_{out} / vbt5) \qquad (4.9)$$

where L_{pred} is the predicted length of the plume, V_{out} is the volume of flow leaving the cross-bank, and vbt5 is as defined above. The volume of flow leaving the cross-bank (V_{out}) during runoff event can also be predicted by equation 4.10:

$$V_{out} = (L / 15)\ V_{15} \qquad (4.10)$$

where L is the RCL – snig track segment of length – that is assumed to be related to the volume of the standard 15-m length segment.

As one of the objectives of the study was to develop a method to reduce the amount of the fieldwork needed for forest road assessment (Chapter 1, section 1.2), an innovative method was used to predict the location of the drainage structures on the road network using GIS approaches. The average distance between the sampled drainage structures was used to define the number of drains that would probably be installed on the roads. The generated point layer was used in conjunction with road, stream, and DEM layers as input layers to predict road-to-stream hydrologic distance (see Chapter 7).

Deterioration of the stream water was defined as occurring where the road-derived runoff and flow pathway had delivered sediment to streams. It was possible to determine whether or not this had occurred by careful field observation of traces of water-flow.

4.7 Development of Erosion Risk Model

Correlation and regression analyses were used to select the most important variables influencing the road erosion and stream deterioration problems, and to assess the possibility of risk associated with the independent variables. Analyses were carried out using STATISTICA versions 5.5 and 6 software (StatSoft, 1999, 2003) and SPSS version 11.5 (SPSS, 2002). The analyses were applied to build models and answer questions related to the hypothesis:

- Are erosion problems found on the surface of the roads or at the outlets of the road drainage structures?
- Which variables (that is, road characteristics and terrain attributes) influence the erosion problems (probability of rill and gullies occurrence)?
- Is there water a flow connectivity between the problematic location and streams?
- Will the sediment, generated from the roads, be delivered to the adjacent streams by a flow pathway?

A combination of quantitative methods was applied during the data analysis and model development. Correlation and ANOVA tests, standard linear regression, logistic regression, and stepwise, pairwise and multiple data comparisons were used to build models to test the individual and group effects of variables influencing the probability of the problems of erosion and stream deterioration.

The outcomes of the analyses were three different models that were built: for the road surface, the outlets of road drainage structures and road-to-stream connectivity. The models were then tested and validated using the fitness validation (goodness-of-fit), Relative Operating Characteristics (ROC) curves, residuals and predictions versus observations. Finally, the models developed from the development data set were applied to the validation data set for validation, as described in Chapters 6 and 7.

4.7.1 Data Preparation

The data compiled by the study consists of two categories: tabular data, including forest road and drain characteristics, and map or spatial data including continuous data sets – terrain attributes, watershed boundaries, stream networks, soil and vegetation types, road and drainage structure maps. Both tabular and spatial data include numerical and non-numerical data. All data must be edited and prepared prior to both GIS-based and statistical analyses. All non-numerical data were transferred to the numerical database by coding (for example, yes = 1, No = 0; valley bottom = 1, midslope = 2 and ridgetop = 3).

The spatial or map data structures were first geographically prepared (for example, projected) and were used for GIS-based analysis. The numeric and non-numeric data relevant to drainage structures and roads were then extracted to create and complete a tabular, spatially explicit database.

4.7.2 Analysing the Data Using Logistic Regression and ANOVA

A. Model Construction

The development data set used for the analysis is a combination of continuous and binomial data. Therefore, logistic regression is the best approach for data analysis and evaluation of the relationship between the variables. In most of the statistical analyses, a combination of simple linear, ANOVA and logistic regression models was used to determine, evaluate and model the best relationship between variables. For example, the relationships between independent variables – for example, CTI, SPI, slope and contributing area – and one or more dependent variables – for example, occurrence of rills and gullies on the surface of the road – were explored using linear and nonlinear functions. However, simple and multiple regressions were used to model and compare the predicted road-to-stream hydrologic distance and estimated slope and hillslope gradients with the actual field-collected data.

What Is the Logistic Regression and How Can It Be Used for Modelling Data?

Logistic regression generally evaluates the relationship between independent variables and a categorical binomial dependent variable. The dependent variable must be binary in nature and can only take values that are 0 and 1, or yes and no. Logistic regression is preferable to the linear probability model because it does not require the OLS-BLUE (Ordinary Least Squared-Best Linear Unbiased Estimator) assumption of normally distributed error terms in multiple regressions (Eastman, 2002; Collett, 2003; StatSoft, 2003). Logistic regression does not generate impossible predicted scores because they are bounded between 0 and 1. Logistic regression uses the assumption that the probability of the dependent variable taking the value of 1 will follow the logistic curve (Eastman, 2002). The logistic regression equation does not directly predict the probability that the indicator is equal to 1: it usually predicts the log odds that an observation will have an indicator equal to 1. The odds of an event are defined as the ratio of the probability that an event occurs to the probability that it fails to occur. The log odds are the natural logarithm of the odds. The probability can be estimated with the formula (Eastman, 2002; StatSoft, 2003):

$$P(Y_i) = \frac{\exp(\sum \beta_i X)}{1+\exp(\sum \beta_i X)} \text{ or } P_i = \frac{1}{1+\exp(-Y_i)} \tag{4.11}$$

where p is the probability of the dependent variable, X is the independent variable and β is the estimated variable. The transformations below are generally applied to linearise the above formula and remove the boundaries (0 and 1). The logistic transformation of p is defined as a natural logarithm of ratio of two probabilities:

$$\text{Logit}(p) \text{ or } P' = \log_e\left(\frac{p_i}{1+p_i}\right) \tag{4.12}$$

$$\text{Log}_e\left(\frac{p_i}{1+p_i}\right) = \beta_0 + \beta_1 * X_1 + \beta_2 * X_2 + \ldots + \beta_k * X_k + \varepsilon_i \tag{4.13}$$

where β_0 and β_i ($i = 1, 2\ldots k$) are estimated parameters and X_i ($i = 1, 2\ldots k$) are independent variables and ε_i is an error term. The method of maximum likelihood is used to estimate the unknown parameters (β_0 and β_i) with the binomial distribution assumed as the error structure of the residuals in the model.

Application in this Case Study

The forward stepwise procedure was first applied by using all independent variables as input in order to analyse, model and find the independent variables best correlated with each dependent variable (for example, rill or gully erosion on the road surface and at the outlet of the road drainage structure, and the road-to-stream connectivity). To do this, independent variables entered the relationships in the order of decreasing linear correlation until there were no significant improvements to the equation statistics. This process was also used to identify the group and individual effects of the independent variables on the probability of erosion occurrence or road-to-stream connectivity.

The analysis was applied to building a model for three different areas of the road. The processes described above – stepwise regression for selecting the independent variables best correlated to the dependent variable – were carried out to model, separately, the probability of erosion occurrence on the road surface and at the outlet of the drainage structure.

B. Testing and Validating the Models

The aim of testing the models developed from the development data set is to determine whether the final models provided a good fit to the data, and to assess the significance of each independent variable to the model. Relative Operating Characteristics (ROC), the goodness-of-fit (GF), multi-resolution goodness-of-fit (MGF), chi-squared, r-squared, and analysis of residuals tests were used for testing and validating the models developed here. A ROC curve generally demonstrates the trade-off between true-positive rate and false positive rate in binary classification problems as a function of varying a classification threshold (Altman, 1991; Pontius and Schneider, 2001). The ROC takes a value of 1 when there is a perfect match between the real data or map and the modelled one, but in cases where there is no spatial agreement between those data or map, the ROC value becomes 0.5. Costanza (1989) suggested that the ROC technique of assessment should be supplemented with additional measures – GF and MGF methods – in order to improve the accuracy of model estimation.

One of the most common assessments of overall model fit in logistic regression analysis is the goodness-of-fit (GF). Goodness-of-fit statistics generally examine the difference between the observed frequency and the expected frequency for groups of variables. The statistic can be used to determine whether or not the model provides a good fit for the data. For the logistic regression model, using maximum likelihood estimation, the likelihood L_0 for the null model where all slope parameters are zero will be compared with the likelihood L_1 of the fitted model (StatSoft, 1999). The chi-square statistics (χ^2) for this comparison can be computed as:

$$\chi^2 = -2 * [\log (L_0) - \log (L_1)] \tag{4.14}$$

To calculate this statistic, the data are divided into 10 groups or deciles. The deciles are composed of data points arranged from those where the model predicts the highest probabilities that the event (in this case rill and gully formation) will occur, to the decile where probability is lowest. For each group, the chi-squared statistic that compares the predicted to observed frequencies (in a 2x10 table) is calculated. Lower values and a non-significant p indicate a good fit to the data and therefore a good fit for the overall model. One such statistic is the Hosmer-Lemeshow goodness-of-fit statistic (Hosmer and Lemeshow, 1989; Collett, 2003).

The goodness-of-fit of the logistic regression can also be calculated using a type of R-squared statistic. Pseudo R-squared is often used to assess the general performance of the logistic regression, when the statistic is affected by autocorrelation. According to Clark and Hoskins (1986), R^2 values above 0.2 are considered a good approximation for logistic regression using maximum likelihood estimation.

Application in this Case Study

Accuracy estimation, testing and validation of the models were carried out using a range of tests. The ROC, the goodness-of-fit or multi-resolution goodness-of-fit, chi-squared, r-squared, analysis of residuals and predictive tests were used to determine whether the final models provided a good fit to the data. These can also be used as appropriate measures of accuracy and simplicity of the final models within logistic regression. Predicted versus observed values and residuals versus expected normal value were also plotted for the final models. The analysis of residuals allows the identification of cases that are poorly fitted and cases that have a great deal of influence on the values of the estimated parameters of the model (Hosmer and Lemeshow, 1989; Collett, 2003). The final validation test of the models was to apply them to the independent 'validation' data set.

In the application of the model to the validation data set, a fitted probability of 0.5 was used as the threshold for acceptance; if the fitted probability was less than 0.5, the model was assumed to predict that there was not a relationship between the variables, if was greater than 0.5, it was assumed that there was a relationship between the variables. To assess accuracy of the models, the predicted values were compared with the actual values recorded from the field. The model will be accepted as validated if the majority of recorded values lie within the predicted 95% confidence interval.

4.8 Risk Assessment and Mapping

The process of risk assessment, both generally and as it is applied to forest roads, was described in Chapter 2, sections 2.1 and 2.2. The following sections describe the application of the process to the case study.

Application in this Case Study

The risk assessment steps and associated processes used in this study are:

Risk Assessment step	**Process**
1 Identifying the risk	1. Stating the risk issues and concerns 2. Mapping rills and gullies associated with roads 3. Predicting and mapping soil loss
2. Analysing the risk	1. Defining likelihood criteria 2. Defining consequences criteria 3. Forming a risk matrix and ranking 4. Defining the risk level
3. Creating risk maps	1. Creating a risk map for each variable 2. Creating an integrated risk assessment map

Each of these components is summarised below. Steps 1 and 2 were carried out separately for each variable influencing the risk associated with the road surface, outlets of road drainage structures, and road-to-stream connectivity. The variables are presented and discussed in Chapters 6 and 7. In step 3, the mapped risk rankings for each variable were aggregated on a spatially explicit basis to create an integrated risk assessment map (Chapter 8).

4.8.1 Identifying Risk

The principal risk on which this study focused was that associated with adverse impacts on water quality caused by erosion from the forest road surface, the outlet of drainage structures, and road-to-stream connectivity. Identifying this risk involved two related processes: mapping the rill and gully erosion on the surface of the roads and at the outlets of road drainage structures (see section 4.3.3), and using the Revised Universal Soil Loss Equation (RUSLE) to build a raster GIS-based model of soil erosion associated with water movement.

Predicting and Mapping Soil Loss Using RUSLE

The Universal Soil Loss Equation (USLE) was developed for estimating the likelihood of soil loss on gently sloping cropland (Wischmeier and Smith, 1978). This equation was further developed by Renard *et al.* (1991, 1997) and adapted for applying to steeper lands and other environments, such as forests, rangelands and disturbed sites. The new version was called the Revised Universal Soil Loss Equation (RUSLE). The USLE and RUSLE are used to make general predictions of soil losses due to erosion from different types of land use –croplands, pasture lands, rangelands, forests and construction sites – at regional, landscape, or watershed scales.

Predicting Soil Loss of the Study Area and Road Network

The RUSLE was used with GIS applications to create an overall assessment of the potential of losing soil from the surface of the study area. The main goal of surface erosion assessment using RUSLE was to provide a preliminary soil loss risk map and to find and map the areas sensitive to surface erosion, and the roads more likely to have rill or gully erosion. The development of the RUSLE model, its application in the case study, and the results from this analysis are presented in Chapter 5.

4.8.2 Analysing the Risk

The risk analysis step involves 4 stages:

1. Defining the level of likelihood, using relevant criteria;
2. Defining the level of consequences, using relevant criteria;
3. Forming a risk matrix which ranks the level of risk for each level of likelihood and consequence;
4. Defining the levels of risk associated with risk rankings, according to relevant criteria.

Risk assessment, analysis and evaluation processes must be general enough to accommodate the various risk factors, and applicable to all possible variables and factors influencing a specific risk arising from a road system. A qualitative risk analysis process was used to assess the risk and define the level of risk of each variable. Criteria for assessing risk likelihood and consequences were defined from the literature, codes of forest practice, and expert knowledge. In this study, mostly qualitative criteria were used to classify roads and the landscape in one of 5 categories – extreme, high, moderate, low or negligible – of risk to water quality. These criteria were used to establish a risk matrix for ranking the risk of impacts on water quality arising from soil erosion associated with forest roads.

Defining Criteria for Likelihood and Consequences

The level of risk is determined by the likelihood and consequences of a particular outcome. The qualitative measures of the likelihood and consequences of the risk for soil and water arising from forest road network are defined in Tables 4.6 and 4.7, respectively. These are adapted from Garvey (1998), AS/NZS (1999), SAA/NZS HB (1999), Boyer *et al.* (1999) and QAS (2002).

Likelihood of occurrence is determined on the basis of estimation of how often an event occurs impacting the elements of risk (in this case, of soil erosion and adverse impact on water quality). Most risk assessors use the terms 'rare', 'unlikely', 'possible', 'likely' and 'almost certain' to rate the likelihood (Garvey, 1998; AS/NZS, 1999; Boyer *et al.*, 1999; QAS, 2002). For example, in the context of forest roads, the likelihood of water quality impacts would be 'likely' or 'almost certain' when the distance between roads and stream is less than 100 m and there is a road-to-stream connectivity (Table 4.6).

Table 4.6. Likelihood categories for risk to water quality from forest roads

Level	Likelihood (Descriptor)	Criteria/Description
1	Rare	An event occurs only in exceptional circumstances. For example, the likelihood of the cross cut-off, collapsing or removing all of the road travelways that is built on gentle slopes or flat areas by gully erosion because of raining or heavy storm events where rebuilding the damaged area is impossible and the route must be changed. The distance between roads and streams is more than 500 m.
2	Unlikely	An event could occur but is not expected. For example, the likelihood of the roads collapsing, gully erosion on the road surface or at the outlets of road drainage structures where the slope gradients are low and the RCA is small. The distance between roads and streams is more than 200 m.
3	Possible/ Moderate	An event could occur. For example, the likelihood of gully erosion on the road surface or at the outlets of the road drainage structures where the slope gradients are gentle but the RCA is large, there are not enough drainage structures installed on the roads or the road drainages are not functioning very well. The distance between roads and streams is more than 100 m.
4	Likely	An event will probably occur in most circumstances. For example, the likelihood of rill or gully erosion on the road surface or at the outlets of the road drainage structures where road is built on steep terrain or the slope gradient is high, the RCA is large, there are not enough drainage structures installed along the roads, and the road drainages are blocked or not functioning at all. The distance between roads and streams is less than 100 m.
5	Almost certain	An event is expected to occur in most circumstances of forest road systems. For example, the likelihood of rill or gully erosion on the road surface or at the outlets of the road drainage structures where road is built on steep terrain or the slope gradient is very high, the RCA is very large, there are no drainage structures installed along the roads, the density of the drains are very low (for example, 1 or 2 drains per each kilometres of the roads), the road drainages are blocked or not functioning at all, the cutslope is not stable or the height and slope of cutslopes are very high, and the roads are not regularly maintained. The surface erosion (rill and gully) during construction or a few years after construction, especially during heavy rainfall or storm events, is very high. The distance between roads and streams is less than 25 m and the slope gradient at the outlets of drains and along the flow pathway is very high.

Consequences are determined based on the elements of risk (in this case, of soil erosion and adverse impact on water quality). Most risk assessors use the terms 'High', 'Moderate' and 'Low' to rate the consequences (Garvey, 1998; NASA, 1998; AS/NZS, 1999; Boyer *et al.*, 1999; QAS, 2002). The consequences and impacts of catastrophic and major events – earthquakes, landslides, mass movements, floods and collapsed access or cut-off the roads – are usually very great and sometimes outside of the control of management systems (see Table 4.7).

Table 4.7. Categories of consequences for risk to water quality from forest roads

Level	Consequences (Descriptor)	Criteria/Description
5	**Catastrophic**	Severe damage including collapsed access to the road, cut-off or high damage on the road and service loss; huge and extensive economic loss; high soil erosion (large rill and gully on the road surface or at the outlets of the drains) and water quality impact (direct sediment delivery to the stream); rebuilding or intensive treatment/ maintenance activities required, but may not be possible to recover in most circumstances.
4	**Major**	Extensive loss, loss of service and production, transport capacity, high soil erosion and water quality impact, high treatment/ maintenance activities required.
3	**Moderate**	High level of damage will result; evidence of rill or gully erosion; there will be sediment delivery to stream; treatment required.
2	**Minor**	The area and amount of damage are small; no major soil erosion or gully or channel formation; no water quality impact by sediment delivery to streams; primary and normal treatment required.
1	**Insignificant**	No damage; no serious soil erosion or rill and gully erosion; no sediment delivery to stream; negligible environmental and economic impacts.

Establishing a Risk Matrix

A risk matrix, developed by combining the defined measures of the likelihood and consequences, is presented in Table 4.8. There are a number of possible approaches to forming the risk matrix, as discussed by Garvey (1991, 1998), NASA (1998), AS/NZS (1999), Boyer *et al.*, 1999, QAS (2002) and UNISON (2005). In this case, the standard approach recommended/adopted by Garvey (1998), AS/NZS (1999), QAS (2002), and UNISON (2005) of generating relative risk scores as the products of the scores assigned to each level of likelihood (L) and consequences (C), was followed.

Table 4.8. Risk matrix for ranking the risk of soil erosion and water quality impacts arising from the forest roads

Likelihood		**Consequences**				
		Catastrophic	Major	Moderate	Minor	Insignificant
		5	4	3	2	1
Almost certain	5	25	20	15	10	5
Likely	4	20	16	12	8	4
Possible/Moderate	3	15	12	9	6	3
Unlikely	2	10	8	6	4	2
Rare	1	5	4	3	2	1

Defining Risk Criteria

The next step in the risk assessment process is to define the risk criteria. Given that the principal objective of this thesis is to evaluate whether the risk of erosion generated from the roads will affect the stream water quality through sediment deposition associated with road-to-stream connectivity, the criteria therefore focussed principally on the possibility of erosion occurrence and road-to-stream distance and connectivity. The criteria presented in Table 4.9 describe the risk associated with each component of the system - road surface, outlets of road drainage structures, and road-to-stream connectivity. They were defined on the basis of the study objectives, the guidelines and codes of practice (Australian Government, 1996, 2000; NLWRA, 2000; AUSTROADS, 2001), the literature (see Chapter 2), field observation and expert assessment of the study area and its road conditions, and the likelihood and consequences criteria (Tables 4.6 and 4.7). Each of the criteria listed in Table 4.9 can be used to define the level of risk for each variable.

Table 4.9. Level of risk and associated criteria for soil erosion and water quality impacts arising from the forest roads

Risk Level	Slope & Road Location	Soil Erosion	Road-to-Stream Distance	Hillslope Gradient	Road-to-Stream Connectivity	Runoff, RCA and USCA	Risk Ranking Scores
Extreme (E)	Road is located on a steep slope.	The erosion rate is very high (>25 tonnes/ha/yr). The probability of rill and gully occurrence is high (there is evidence of large gully erosion).	The road is located close to a watercourse (distance 0 to <60m (valley bottom)) and runoff generated from the road delivers directly to the streams.	Slope value at the drainage outlet downward to the stream is very high (>30%).	There is a gullied connection between roads and streams.	The volume of runoff delivery to the streams is high because of the big RCA (>150 m^2) and USCA, especially during storm events.	12-25
High (H)	Road is located on a steep slope	The erosion rate is high (15-25 tonnes/ha/yr); there are evidences of gully erosion.	The road is located close to streams (<80m) and the runoff delivers directly to the streams.	Slope value at the drainage outlet downward to the stream is high (20-40%).	There is a gullied connection between roads and stream.	The volume of runoff delivery to the streams is high because of the big RCA (between 70 - 150 m^2) and USCA.	7 - 11
Moderate (M)	Road is located on gentle slope.	The erosion rate for this category is not very high (5-15 tonnes/ha/yr); there are evidences of rill or small gully erosion.	The road is located near to streams (60-100m) and the runoff may deliver to the streams.	Slope value at the drainage outlet downward to the stream is not high (15-25%).	Most runoff delivery and road-to-stream linkages are diffused connections.	The volume of runoff delivery to the streams is not big because of small RCA (between 40 - 70 m^2) and USCA.	4-6
Low (L)	Road is located on lower slope and flat areas	The erosion rate is low (1 - 5 tonnes/ha/yr); there may evidences of rill erosion, but there is no evidence of gully erosion.	The road is not located close to streams (>120m) and the runoff is less likely to be delivered to the streams.	Slope value at the drainage outlet downward to the stream is small (5-20%).	Almost all runoff delivery and road-to-stream linkages are diffuse connections or there is no connection between roads and streams.	The RCA is mostly less than 40 m^2 and USCA is small.	1-3
Negligible (N)	Road is on a very flat area	The erosion rate is low and/or very low (0 - 1 tonnes/ha/yr); there is no evidence of rill or gully erosion.	The road is located far away from streams (>300m) and the runoff does not reach the streams.	Slope value at the drainage outlet downward to the stream is small (0 - 10%).	There is no road-to-stream hydrologic connection except during very heavy storm events, as diffuse connectivity.	The RCA is less than 20 m^2 and USCA is very small.	≤1

The principle features of each risk categories (Table 4.9) are:

- In the extreme risk category, rills are likely to form on the road surface or at the outlets of the drainage structures in most years and gullies may develop in very wet periods. The runoff with associated sediment is likely to reach the streams;

- In the high risk category, rills are likely to develop in most seasons during wet periods, but gullies may develop only during very wet periods. Runoff with associated sediment is likely to reach the streams;
- In the moderate risk category, rills may develop in some seasons during very wet periods, sediment may be seen running from the road surface and ditches, but it is less likely to reach the streams;
- In the low risk category, small rills will rarely develop, sediment is rarely seen to move, and runoff is less likely to reach the streams; there is less likely to be road-to-stream connection, and the connection is always through diffuse linkages;
- In the negligible risk category, there is neither rill development nor sediment movement on the road surface or at the outlets of the drainage structures; there is no road-to-stream connection.

Evaluating the Risk Associated With Risk Rankings

The risk associated with each variable for each component of the system - road surface, outlets of road drainage structures, and road-to-stream connectivity - was ranked using the risk matrix (Table 4.8). The process described in section 4.8.2 was followed for each variable influencing the risk of sheet erosion occurrence on the road surface, at the outlets of road drainage structures, and road-to-stream connectivity; this assessment is described in Chapters 6 and 7.

The risk ranking for each variable was also assigned a risk level, based on the scale for individual variables presented in Table 4.9. Each of these data sets of numerical risk ranking represented a layer in the GIS database. Risk rankings for each variable were then summed, on a spatially explicit basis, to calculate the aggregate risk score for each pixel, and the aggregate ranking was assigned a risk level on the basis of the scale described in Table 4.6. As seen in Table 4.9, there were 5 categories of risk level, from extreme to negligible.

4.8.3 Creating a Risk Map for Each Variable

The numerical risk rankings for each variable, derived as described above, were aggregated to create a risk component map. Each risk component map can include one or more variables. One example of the risk component that included just one risk variable is that for RUSLE. An example of a risk component which included more than one variable is that for road-to-stream connectivity which comprises aggregated risk variables of hillslope gradient, RCA, USCA and road-to-stream hydrologic distance.

Integrating the Risk Assessment into a Consolidated Map

The overall risk associated with the forest road network, assessed by the probability of sediment delivery to the stream, can be ranked and shown in an integrated risk map. To construct this consolidated risk map, all of the individual ranked risk maps were combined using GIS overlay applications (that is, intersection and Multi-Criteria Evaluation (MCE), as described in Chapter 2, section 2.2.1).

The variables were aggregated by adding the single score for each are in each pixel to generate an aggregate score for each component. The final score of each risk level depends on the number of the risk variables and components used to create the final consolidated risk map. In each case, it will be the sum of the total given score to each risk according to the level of the likelihood and consequences. For example, the total score for risk level ranked as 'high' for gully connectivity between roads and streams would be the sum of the given score for the rill and gully erosion, hillslope gradient, distance between roads and streams, RCA, and upslope contributing area, as the variables influencing the risk. Interpretation of the final consolidated risk map gives information on the elements at risk, and can be used as a tool for managing the forest road system. The implications and results of the risk assessment are described in Chapter 8.

4.9 Summary and Conclusions

The method used in this study is to combine data on soil erosion and water quality impacts generated by the forest roads within a pine plantation. It employs spatial data on the road layout and drainage structures, and predicts the possible connectivity between the road drainage structure and stream channel network.

The study proceeded in several steps: map preparation, experimental design and field survey, DTM analysis, forest road analysis and establishing a comprehensive integrated road database. From these data, slope position and stability analysis, landform analysis, watershed delineation, are calculated and the hydrologic distance between roads and streams, and road-to-stream connectivity assessment are modelled. A risk model developed using logistic regression and other statistical analyses, was used for risk assessment and mapping including predicting soil loss by applying RUSLE, and creating a risk map. DPGS and GIS were the main tools used in gathering data and analysing and preparing the necessary maps and risk components for the evaluation processes of the study. The GIS software used for analysing and evaluating the data were ArcGIS, ArcView, IDRISI, ERDAS, FGIS and MAPWin.

Determining the probability of a hydrologic connection between forest road drainage structures and streams is important to the risk assessment of forest roads. To do this, topographically determined, GIS-based models were applied to predict flow pathways (the hydrologic distance between the outlet of the road drainage structures and the streams). The terrain attribute layers resulting from DTM were used as input data for this prediction. Then logistic regression, threshold values and field observations were used to define the road-to-stream connectivity.

The approach used in this study to determine the factors influencing the erosion and water quality impacts on unsealed forest roads entailed using both quantitative and qualitative analytical processes. Statistical analyses, mostly logistic regressions, were used to evaluate the data.

The aim of this method was to develop and introduce a GIS-based process and procedure which can be used to combine different methods and procedures of assessing the risk from different parts of the road network, in order to visualise and map the overall risk arising from the roads to the soil and water.

The procedures, processes and results of the GIS applications, methods, techniques and statistical models used will be presented and discussed in Chapters 5, 6 and 7. The results of implementing the RUSLE, to provide an overview of the area and its road network in terms of soil loss condition, will be presented in Chapter 5. The results of terrain analysis and model development for predicting rill and gully occurrence on the road surface and at the outlets of road drainage structures will be presented and discussed in Chapter 6. In Chapter 7, the results of road and watershed analyses and road-to-stream connectivity modelling and risk assessment will be discussed. The final risk map, presented in Chapter 8, is a consolidated map of different risk components evaluated by both GIS and statistical analysis.

Chapter 5
Results and Discussion 1: Estimating Relative Soil Erosion Using the Revised Universal Soil Loss Equation (RUSLE) and GIS Techniques

5.1 Introduction

Before the effect of erosion from road systems can be determined, the amount of soil loss must first be estimated. If soil loss is negligible, then the risk to streams will also be negligible. Conversely, in situations where erosion is predicted to be moderate to severe, sedimentation will be likely, but only if there is a water-flow connection between the road and the nearest stream. The Revised Universal Soil Loss Equation was used to indicate those places along the road network where erosion from the road surface could be expected to be moderate or greater. Field inspection confirmed the general accuracy of the prediction and showed that the study area contained sufficient variation in soil erosion potential to be a suitable experimental area. It also demonstrated the likelihood that soil erosion could be predicted using established theory and GIS technologies.

As described in Chapters 2 and 4, sections 2.3.9 and 4.8.1, the USLE and RUSLE are empirical models used to make general predictions of soil losses due to erosion at regional landscape or watershed scales. However, they may be better at predicting relative rather than actual amounts of soil loss. Rosewell (1993) and Edwards (1986) argued that USLE may be applied to different types of land use, such as croplands, pasture lands, rangelands, forests and construction sites. In the present research, the RUSLE has been used to estimate the volume of soil loss in the study area, and to categorise and evaluate the risk of soil loss and erosion from forest roads.

The RUSLE equation comprises a linear combination of factors:

$$A = R * K * L * S * C * P \quad (5.1)$$

where: A is the annual average soil loss in tonnes per hectare per year, and shows the prediction of possible soil losses across the catchment area; R is the rainfall erosivity and runoff factor in Mega joules per millimetre per hectare per year, which is the number of rainfall erosion units; K is the soil erodibility factor in tonnes per hectare per year; L and S are topographic factors, where L is the slope length factor in metres and S is the slope steepness factor in percent; C is the land cover management factor; and P is the support practice factor.

The accuracy and reliability of predictions by the model depend on the precision in calculating each individual factor, and also on the way in which the individual factors are combined when running the RUSLE model. The soil erodibility (K-Factor), slope length (L) and slope gradient (S) should be estimated or calculated as accurately as possible, as any miscalculation will directly affect the result of soil loss prediction.

The main goal of surface erosion assessment using RUSLE, as part of a catchment and road assessment, was to provide a preliminarily risk map with an understanding of:

- Which areas of Stromlo Forest are sensitive to surface erosion?
- Which road segments are located in sensitive areas, in terms of losing soil?
- What is the possibility of surface erosion (rills and gullies) on the surface of the roads, in terms of the soil loss risk ranking?
- Which parts of forest roads are more likely to have rill and gully erosion?
- What is the condition of the hillslope between roads and streams in terms of erosion sensitivity?

These questions will be answered by developing a soil loss map of the study area and its forest road network. The answers will provide an overview of the area and its road network, which will be used for the detailed studies of the roads and of the hillslopes between roads and streams.

5.1.1 The Use of RUSLE for this Project

The four major factors affecting sheet, rill and inter-rill erosion are climate, soil, topography and land use. Since erosion is inherent in the properties of soils and slope gradient, any method for mapping erosion must consider these properties. The RUSLE (Renard *et al.*, 1991, 1997) is such a method, which considers all of these factors. This model is contained in an exceptionally well-validated and documented equation (Toy *et al.*, 1998). RUSLE retains the structure of its predecessor, the USLE (Wischmeier and Smith, 1978). RUSLE is a very powerful tool that is used to estimate soil loss under a wide variety of site-specific conditions. The use of this model is limited to the estimation of gross erosion, because it lacks the capability to compute deposition along hillslopes, depressions, and valleys or in channels. In addition, as erosion can occur only along a flow line without influencing the water flow itself, this restricts direct application of the USLE to computations within GIS. Although the RUSLE can be used as a GIS based model, there are still some limitations and some processes must be calculated manually.

As mentioned above, soil erosion is influenced by the spatial heterogeneity in topography, vegetation, soil properties and land use. As GIS has the capability to examine the problem in a spatial context, coping with a large volume of spatial data (Haining, 2003) and the relationship between data from various sources in the erosion modelling process, it therefore becomes a valuable tool that can be used in conjunction with RUSLE. In comparison with predictive soil erosion models, the RUSLE shows approximately what percentage of the basin and forest roads are in erodible soils and thus determines the possibility of potential soil loss or occurrence of erosion in the specific area. Visual evidence of erosion in the field, such as rills and gullies, can be used as evidence to validate the possibility of soil erosion occurring.

The user must ensure that RUSLE is applied to appropriate soil-loss problems, and that inputs for the calculation of factor values accurately represent site conditions. The RUSLE model can also be adapted to estimate road surface erosion (EPA, 2000). This typically requires some expertise and familiarity with conducting erosion studies. A GIS system is also very helpful for simplifying many of the steps for calculating the related factors. The

RUSLE is best used on smaller drainage basins by dividing the basin into areas of uniform soil type, topography, and agronomic conditions (EPA, 2000). The soil loss can then be computed for each combination, and this can be greatly simplified if GIS is used. Erosion potential prediction has become a widely applied GIS operation, and the integration of GIS with erosion models has been addressed in several studies (De Roo *et al.*, 1996; Desmet and Govers, 1996; WEPP, 1999; Croke and Mockler, 2001; NCASI, 2002; IDRISI, 2004).

The RUSLE can be used to predict the amount of soil moved from its original position but does not necessarily predict the amount of sediment transported out of an area or watershed (EAP, 2000). Sediment delivery into an adjacent streamline or other sediment-transport conduits such as gullies, ditches and channels can be considered to be a separate step. Sediment delivery correlates with hillslope gradient and infiltration rates on bare soils but can be best predicted by slope length and soil erodibility on vegetated surfaces (Ebisemiju, 1990). Reid and Dunne (1996) found that redeposited sediment is mostly related to factors such as gradient, surface roughness, vegetation cover, storm runoff, and distance from the sediment source (that is, roads). These parameters should be noted when a field survey is conducted in order to identify the conditions under which delivery may be significant.

Road surface erosion is generally evaluated separately from sheetwash erosion because of the former's importance (Reid and Dunne, 1996). A number of factors can affect the production of sediment from roads – road surface conditions and surfacing material, traffic levels, rainfall, and drainage structure and design. Road erosion is typically of greatest concern at stream crossings, although roads parallel to streams can also cause sedimentation problems (EAP, 2000). Watershed-scale road erosion is typically evaluated by developing an average annual rate of erosion multiplied by the area of road delivering sediment directly to streams.

The 'Background Erosion' Rate and Its Relationship to This Project

All lands are subject to "background" erosion, viz. the natural erosion of any surface, which occurs on all managed and unmanaged land, including forested areas. Background erosion and sedimentation rates are generally estimated when it is necessary to partition the total sediment deposited in a stream into sources, such as erosion from the stream banks, the riverbed itself, or the effects of management.

The case study area has rolling topography and is situated in an area of relatively low rainfall (c. 640 mm per year, see full description of the study area in Chapter 3). These factors mean that the background soil loss rate will be small by international standards; furthermore, under typical Australian conditions, only 5 – 10% of the background hillslope erosion will reach the streams by the process known as 'natural movement' (Prosser *et al.*, 2001).

For these reasons, background soil loss was not considered further in the development of models in this study. If a similar study were to be conducted in an area with a high background rate of soil loss, and/or where a greater proportion of background erosion reaches the streams, background soils loss rates would be relevant to model development and application.

Preliminary Exploration of the Application of RUSLE to the Case Study Area

Although RUSLE was originally developed as a method of predicting comparative soil loss from different agricultural practices, the model has been used to examine effects in forests since at least 1997. The chosen study site is typical of plantation forests in the ACT. RUSLE was used to predict the probability of different erosion rates occurring on forest roads and related hillslopes. The results were compared with erosion as visually assessed in the field. In locations where 'high' erosion was predicted by the model, there was evidence of considerable erosion, such as the presence of rills and gullies. There was a good correlation and agreement between actual location predicted to have high erosion probability and what was seen in the field. For the areas classified as having negligible soil erosion, there was no evidence of any more than minor erosion.

The preliminary observations provided confidence to continue the study using other techniques and models to quantify and describe the erosion delivery process to streams, and a method based on accepted principles controlling soil loss appeared to be valid for this site. It also meant that the site was suitable for this investigation because it showed clear examples of variation in soil erosion and that these were associated with loss predicted by a well-accepted model.

5.2 Application of RUSLE Model Using GIS

The RUSLE model can be implemented and the amount of soil lost from a specific catchment area can be calculated using the overlay and multiple criteria evaluation functions present in almost all GIS software. The equation factors are set up as GIS layers in a grid format in order to calculate and classify the soil loss. Each layer is created individually and then the layers are overlayed and accumulated, resulting in the average annual soil loss layer. This makes it possible to develop spatial soil loss and soil erosion models.

The application of RUSLE using the IDRISI software is summarised in Box 5.1. However, the RUSLE modelling provided in the IDRISI software did not prove to be well suited to the purpose of this study because of the intensity of the work required to define the relevant RUSLE thresholds. In particular, selecting the correct slope and aspect thresholds and the smallest patch size, were problematic in running this model in IDRISI.

Box 5.1. Steps in implementing the RUSLE model using IDRISI

1. Determine the value of Rainfall and Runoff Erosivity (R-Factor).
2. Determine the soil erodibility (K-Factor) based on the soil series or texture.
3. Determine the land cover management factor (C-Factor) and support practice factor (P-Factor).
4. Prepare an accurate and high resolution DEM.
5. Determine and select a proper slope, aspect and patch size thresholds.
6. Run the model in order to obtain soil loss rate within the patch and the catchment (the study area) in ton/ha/year.

Note: All layers must be built in IDRISI (image) raster format.

Consequently, RUSLE assessment was implemented for the study area and its road network using ArcGIS software. The processes of calculating and creating each factor and GIS layer related to the estimation of soil loss in the Stromlo Forest are summarised in Box 5.2. The application was carried out for the SFMA and adjacent land within the study catchment area, which totals nearly 10,500 hectares. Running this model resulted in an estimate of relative soil erosion. The values do not equal the amount of sediment production or sediment transport to stream in the study catchment area, but are rather an index of those values. The processes involved in implementing the RUSLE in ArcGIS and IDRISI are different (Boxes 5.1 and 5.2); to run the model in ArcGIS, all layers must be created separately.

Box 5.2. Steps in implementing the RUSLE model using ArcGIS

1. Determine the value of Rainfall and Runoff Erosivity (R-Factor).
2. Determine the soil erodibility (K-Factor) based on the soil series or texture.
3. Determine the present slope (S-Factor).
4. Determine/measure the length of slope (L-Factor).
5. Measure/calculate the LS-Factor.
6. Determine the land cover management factor (C-Factor) and support practice factor (P-Factor).
7. Overlay/multiply the factors in order to obtain soil loss rate within the catchment (study area) in ton/ha/year.

Note: All layers must be built in Arc grid format.

For forest roads, the model was run separately using the road database and information as input layers. A grid layer of road network with field-measured slope value was created using ArcGIS. This layer was then used as input to calculate the S, L and, finally, LS factors of the roads. Other related factors were created individually for forest roads and then were used as road input layers to run the RUSLE model. The output of the model application using ArcGIS is a grid layer combining the different factors. The amount of soil loss and soil erosion can be extracted using grid commands from the grid layer for the forest road layout or for the location of the road drainage structures.

5.2.1 Rainfall and Runoff Erosivity Factor (R-Factor)

The rainfall and runoff factor (R-Factor) is a measure of the erosive power of rain. The R-factor index varies from one location to another and its calculation is based on the kinetic energy of the annual summation of rainfall that correlates with raindrop size. Total energy and the maximum 30-minute intensity of storms (EI_{30}) have been defined as two component factors for the R-Factor calculation (Wischmeier and Smith, 1978). The total storm kinetic energy (E) is estimated from rainfall intensity: each region has a different equation for E calculation. Rosewell (1986) developed an equation for calculation of E under Australian circumstances:

$$E = 29.0\ (1 - 0.596\ \mathrm{Exp}\ (-0.04I) \qquad (5.2)$$

where E is storm energy or erosion index in $MJ/m^2.mm$ and I is the rainfall intensity in mm/h. The R-Factor has been estimated for all Australian states, including, New South Wales (NSW), which itself includes the Australian Capital Territory (ACT), by Rosewell (1986, 1993) and Bureau of Rural Sciences (2000). The range of the calculated R-Factor for the ACT is 234-1697 $MJ.mm/\ ha^{-1}.h^{-1}.y^{-1}$, with an average of 858. Wischmeier (1959, 1976, 1978) argued that the best prediction of R-Factor is:

$$R = \frac{1}{n}\sum_{j=1}^{n}\left[\sum_{k=1}^{m}(E)(I_{30})_k\right] \qquad (5.3)$$

In equation (5.3), E is the total storm kinetic energy in hundreds of (metric) tonnes per hectare, I_{30} is the maximum 30-minute rainfall intensity, j is the counter for each year used to produce the average, k is the counter for the number of storms in a year, m is the number of storms in n years, and n is the number of years used to obtain the average R. The amounts of rainfall and peak intensity are the two most important characteristics determining the R-Factor.

The rainfall and runoff erosivity index for running the RUSLE for Stromlo Forest were adopted from Rosewell (1986, 1993) and from the R-factor predictions for all Australian states (Bureau of Rural Sciences, 2000). The R-factor data and map of the study area (Stromlo Forest) have been extracted from the R-factor map of Australia (Bureau of Rural

Sciences, 2000), which was downloaded from the Bureau of Rural Sciences (2000) and the Australian National Resources Data Library (Bureau of Rural Sciences, 2000). The map was projected, categorised and analysed in order to create the single categorized layer for the model. A summary of statistical parameters of the R factor of the study area, in MJ.mm/ $ha^{-1}.h^{-1}.y^{-1}$, is shown in Table 5.1. As can be seen from Table 5.1, the average value of the R factor of the study area (1528) is nearly twice that of the average value for the whole of the ACT (858).

Table 5.1. The R-Factor parameters (MJ.mm/ $ha^{-1}.h^{-1}.y^{-1}$) of the study area

Area (ha)	Minimum Value	Maximum Value	Mean Value	Standard Deviation	Range
10477	1252	1683	1528	80	431

The R factor value of the forest roads located in the Stromlo Forest was extracted using ArcInfo commands. Table 5.2 is a statistical summary of the R-Factor of the forest road network of the study area. Although the distribution of the mean value of the R-Factor is 3 points less than the mean value of the catchment area, the minimum and maximum values are almost identical.

Table 5.2. The R-Factor parameters (MJ.mm/ $ha^{-1}.h^{-1}.y^{-1}$) of the forest roads in the study area

Road Length (km)	Minimum Value	Maximum Value	Mean Value	Standard Deviation	Range
307	1253	1683	1525	74	430

5.2.2 Soil Erodibility Factor (K-Factor)

Rosewell (1993) defined soil erodibility as a measure of susceptibility of soil to erosion. The determination of the soil erodibility factor (K) of the study area is based on the soil texture, that is, the relative presence of sand, silt and clay. Generally, sandy soils have low K values because of their coarse texture and low-level runoff. Clayey soils have low K value because of their detachment resistance. Susceptibility of the soil to detachment can be reduced by the percentage of organic material; the amount of runoff and erosion will therefore decrease when infiltration rates are increased. This determination was based on the SOILOSS program written by Rosewell (1993) for Australian conditions. To apply this to the study area, the texture of each soil type was first listed based on the soil map of the Canberra district (Sleeman and Walker, 1979), and the K-Factor values were determined using the soil erodibility nomograph (Foster *et al.*, 1981) in SI units (Figure 5.1).

According to the SOILOSS handbook (Rosewell, 1993), the erodibility nomograph determines accurately the soil erodibility factor (K) for soils containing less than 70 percent silt plus very fine sand (0.002 – 0.1 mm). McKenzie *et al.* (2004) argued that soil organic matter is the sum of the biologically derived organic materials found in the soil; this is measured by the content of organic carbon. If the organic carbon level is less than 1%, the organic matter is small and if it is greater than 2%, the level of organic matter is considered high (McKenzie *et al.*, 2004); (1-2% is considered moderate).

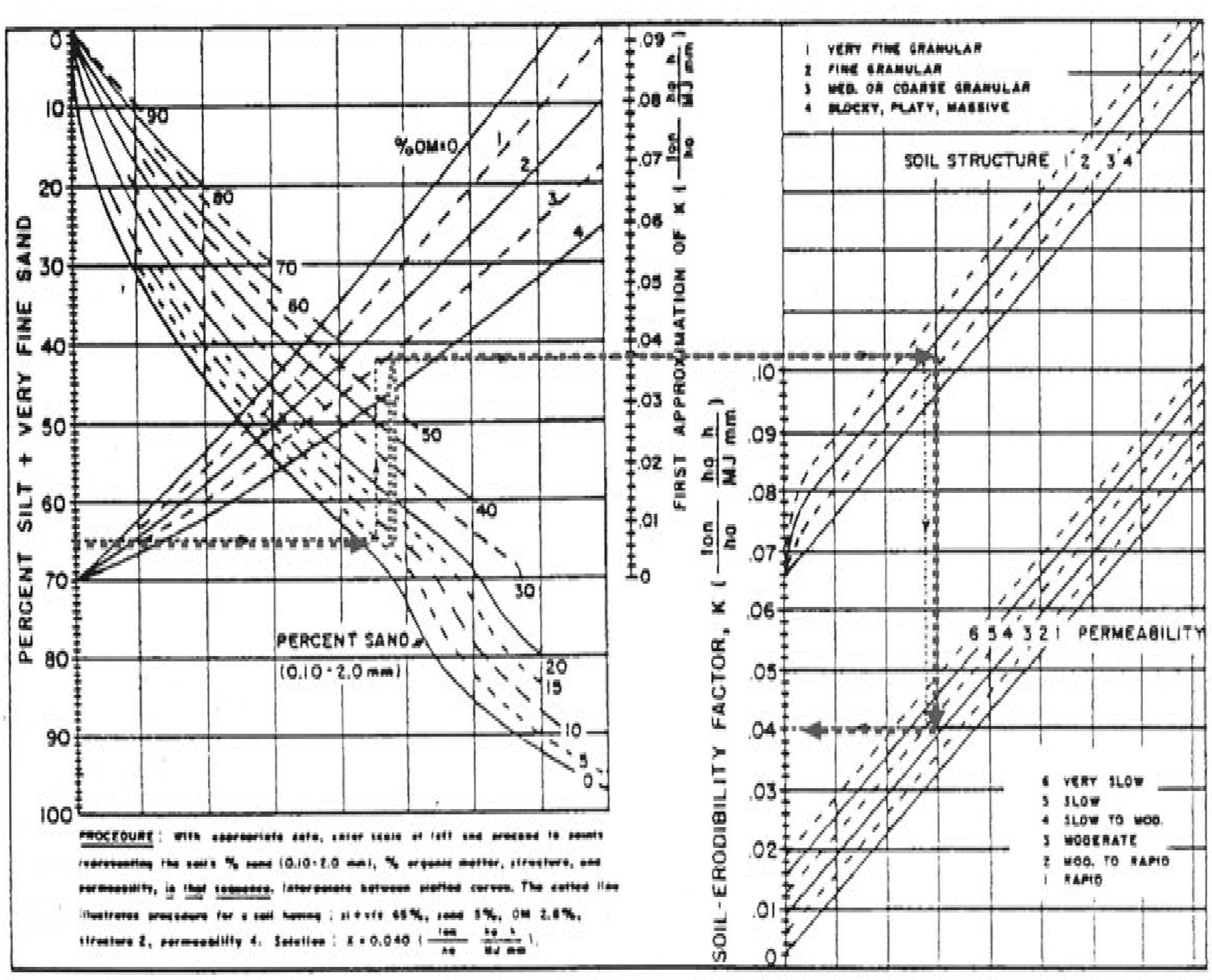


Figure 5.1. Soil erodibility (K-Factor) nomograph in SI units

Source: Adapted from Foster *et al.* (1981)

The procedure for determining the K value using the nomograph is: (1) the relative percentages of silt and very find sand, sand (0.1 – 2 mm) and organic matter are first calculated or determined; (2) soil structure classes; and (3) permeability level are then determined. In Figure 5.3, a blue dotted line (arrow) illustrates an example of K value determination. The values of silt and very fine sand, sand, organic matter, structure and permeability are 65%, 5%, 2.8%, 2 (fine granular structure) and 4 (slow to moderate permeability), respectively, in this example. As can be seen from Figure 5.1, the K-Factor value in this example is 0.04 tonnes per ha per year. The permeability level was determined for the forest road with reference to the road condition and the level of road use.

Table 5.3. Summary of the K-Factor parameters of the study and the forest roads

Parameter	Area (ha) or Length (km)	Minimum Value	Maximum Value	Mean Value	Standard Deviation	Range
Study Area (ha)	10477	0.033	0.051	0.044	0.0015	0.018
Roads (km)	307	0.033	0.057	0.046	0.0006	0.019

The K value will always be greater than 0 and less than 0.1 (in SI units). K< 0.02 indicates low soil erodibility, 0.02 – 0.04 moderate and K >0.04 indicates high soil erodibility (Rosewell, 1993). Based on Rosewell's (1993) categorisation of K value for Australian regions, about 97% (10,155 ha out of 10,477 ha) of the study area and 88% of forest roads were classified as having high, and about 3% and 12% as having moderate, soil erodibility, respectively (Table 5.4). Hence, the minimum and maximum estimated values of the K-Factor for the study area and forest roads are between 0.033 and 0.057 (Table 5.3); therefore, the rate of soil erodibility (risk) of the study area and roads can be categorised as moderate to high.

Table 5.4. Soil Erodibility ($t.ha^{-1}.y^{-1}$) classification of the study area and the forest roads

K Value	<0.02; Low Soil Erodibility	0.02 – 0.04; Moderate Soil Erodibility	>0.04; High Soil Erodibility
Area (ha)	0	322	10155
Percent	0	3.1	96.9
Roads (km)	0	37	270
Percent	0	12	88

5.2.3 Topographic Factors (LS-Factor)

Topographic factors include hillslope length (L) and slope steepness (S). A combination of L and S factors is known as the LS factor. This is one of the more significant component factors of USLE and RUSLE. Where field measurements are not feasible, the LS factor can generally be estimated from a DEM layer. However, while extensive computer programming has been developed for a RUSLE GIS-based grid in many GIS software packages, including ArcInfo and IDRISI, there are still some difficulties in obtaining very accurate LS factors.

The slope length factor (L-Factor) is expressed (Zingg, 1940 cited in Liu *et al.*, 2000:1759) as:

$$L' = a\lambda^{m} \tag{5.4}$$

where L' is soil loss per unit area per unit time, λ is slope length in metres, and a and m are empirical coefficients. This equation can be normalised to a unit plot of length 22.13 metres for both USLE and RUSLE (Liu *et al.*, 2000).

$$L = (\lambda / 22.13)^{m} \tag{5.5}$$

where L is soil loss normalised to the unit plot of length 22.13 metres and m is empirical coefficient. One of the main differences between USLE (Wischmeier and Smith, 1978) and RUSLE (Renard *et al.*, 1991, 1997) is the differences between the values of m suggested by USLE and RUSLE. The suggested m values for the USLE (Wischmeier and Smith, 1978) were 0.2, 0.3, 0.4, and 0.5 for the slope gradients <1, 1 to 3, 3.5 to 4.5, and 5% or greater, respectively (Liu *et al.*, 2000). A problem with this categorisation occurs when the slope gradient exceeds 5%: the slope length factor for soil loss calculation using the USLE does not change with the slope steepness. This problem has been solved in the RUSLE model, where the m value is considered as a continuously increasing value, using the equations below (Renard *et al.*, 1997):

$$m = \beta / (1 + \beta) \quad (5.6)$$

$$\beta = (\sin\theta / 0.0896) / \left[3.0(\sin\theta^{0.8}) + 0.56\right] \quad (5.7)$$

where β is the ratio of rill erosion to inter-rill erosion, and θ is the angle of the slope gradient.

The value of the hillslope length factor is 1 for a unit plot (normalised) 22.13 metres in length with a hillslope gradient of 9% (Renard *et al.*, 1997; Toy *et al.*, 1998). The L-Factor value will be less than 1 for hillslope lengths less than 22.13 metres and more than 1 for slope lengths greater than 22.13 metres. The hillslope length (L-Factor), hillslope gradient (S-Factor), and LS-Factor of the study area were calculated using an ArcInfo AML, which was originally written by Rick *et al.* (2003). The AML was adapted for the study area in order to consider its characteristics and to create, separately, the GIS layers for the S and L factors and the LS factor combination.

As hillslope gradient and length increase, the total soil loss in a catchment area increases because the velocity, erosivity and the progressive accumulation of runoff increase in the downslope direction.

Table 5.5. Summary of L-Factor parameters of the study area and the forest roads

Parameter	Area or length	Minimum Value	Maximum Value	Mean Value	Standard Deviation	Range
Study Area (ha)	10477	0.64	2.6	1.06	0.28	1.96
Roads (km)	307	0.62	2.27	1.08	0.30	1.63

Table 5.6. Summary of S-Factor parameters of the study area and the forest roads

Parameter	Area or length	Minimum Value	Maximum Value	Mean Value	Standard Deviation	Range
Study Area (ha)	10477	0	12	1.3	1.3	12
Roads (km)	307	0.05	9.1	1.5	1.2	9.1

Tables 5.5 to 5.7 present summaries of parameters for L and S factors of the study area and forest roads. The minimum value of the L-Factor is 0.64 and 0.62, and maximum value is 2.6 and 2.27, for the study area and forest roads, respectively (Table 5.5). As can be seen in Table 5.6, the minimum and maximum values of S-Factor are 0 and 12, respectively, while

these values are 0.05 and 9.1 for forest roads. From Table 5.7, it can be seen that more than 95% of the S-Factor of the forest roads and less than 95% of this value for the study area are distributed between the values of 0 – 4. Higher values of the S-Factor (4 – 12) occupy more than 5% and 3% of the study area and forest roads, respectively.

Table 5.7. Summary of the distribution of the S-Factor in the study area and the forest roads

S-Factor	0 – 2	2 – 4	4 – 6	6 - 8	8 – 12	Total
Number of pixels	220102	29588	9806	1811	618	261925
Area (ha)	8805	1184	392	72	25	10477
Percent	84	11	4	1	0.2	100
Roads (km)	249	48	7	3	0.1	307
Percent	81	16	2	1	0	100

Table 5.8. Summary of LS-Factor parameters of the study area and the forest roads

Parameter	Area or length	Minimum Value	Maximum Value	Mean Value	Standard Deviation	Range
Study Area (ha)	10477	0.05	24.4	1.4	1.6	24.4
Roads (km)	307	0.05	16.3	1.7	1.7	16.2

Table 5.9. Summary of the distribution of the calculated LS-Factor in the study area and the forest roads

LS	0-0.05	0.05-1	1-2	2-3	3-5	5-10	10-15	15-20	20-24.4
Number of pixels	77899	66063	61755	23802	22143	9594	863	104	10
Area (ha)	3116	2642.5	2470.2	952.1	885.7	383.8	34.5	4.16	0.4
Percent	30	25	24	9	8	4	0	0	0
Roads (km)	19	116.5	121.56	22.1	17.5	7.3	3	0.6	0
Percent	6	38	40	7	6	2	1	0	0

Tables 5.8 and 5.9 present the summary of parameters for the LS-Factor of the study area and forest roads, respectively. The minimum value of LS-Factor is the same (0.05) for the study area and forest roads, but the maximum and means values are 24.4 and 1.4 for the study area and 16.3 and 1.7 for the forest roads, respectively (Table 5.8). Table 5.9 summarises the distribution of the calculated LS-Factor of the study area and the forest roads. From Table 5.9, it can be seen that more than 96% of the LS values are distributed around the mean value (between 0.05 and less than 5) for both the study area and forest

roads. Greater values of the LS-Factor (5 – 24.4) occupy less than 4 and 3% of the study area and forest roads, respectively. Only some small patches, totalling about 5 hectares (0.04%) of the study area, and 0.6 km of the roads, have a value of 15 – 24.4 LS-Factor.

5.2.4 Land Cover Management (C) and Support Practice (P) Factors

The land cover management factor (C-Factor) represents the effects of land cover (vegetation) management, and also control practices for soil erosion and soil loss. The C-Factor can be interpreted by calculating the ratio of soil loss from the specific land use example to the corresponding soil loss from continuously tilled bare fallow (Rosewell, 1993). The soil loss ratio is also an estimate of the ratio of soil loss under different reference conditions. This ratio varies with canopy, density of surface cover, plant litter and soil biomass, surface roughness and any consolidation change. The C-Factor is generally derived from the combination of soil loss ratios and the applicable percentages of erosion index (EI) (Rosewell, 1993). The C-Factor value shows how the land use management plan will affect the average annual soil loss and the potential soil erosion distribution for a particular management system. The C-Factor is also expressed as an annual value for a particular management plan or management practice.

The land cover management factor (C-Factor) is dimensionless and varies from 0 – 1 depending on the situation – for example, canopy cover, mulch cover, residual trees and management effects (Rosewell, 1993; University of Zululand, 2001, 2003). The estimated C-Factor for the study area was based on the C-Factor classification for permanent forest, pasture and rangeland, or scrub (Rosewell, 1993), and the situation after the 2003 bushfire. It is clear that the density of canopy cover, including both top level cover (trees) and ground cover, was suddenly destroyed by the bushfire. However, the residual burnt trees and recovery management after the fire, including removing trees, site preparation, and regrowth or revegetation of grasses, ground cover and trees, increased the percentage of total ground cover in contact with the soil surface a short time after the bushfire event. A unique value of land cover management factor (C-Factor = 0.076) was therefore estimated for the study area. This was done following the guidelines and processes developed by

Rosewell (1993) and reported in the SOILOSS Handbook, which considers the percentage of the canopy cover remaining, including ground cover – grasses, weeds and shrubs – and land cover under recovery management.

A support practice, known as the P-Factor, represents the effects of a specific management practice on soil loss under standard conditions. The P-Factor is also defined as the ratio of soil loss when a support practice such as contour cultivation or contour tillage, furrowing and ripping, diversions and contour vegetation strips is used, compared with cultivation up and down the slope (Rosewell, 1993). According to Schulze (1989) and Rosewell (1993), the P-Factor is dimensionless, varying from 0 to 1. Contour cultivation is most effective on slopes between 3 – 8 percent and the P-Factor, and the soil loss ratio in this situation, compared to cultivated land that is tilled directly up and down slope, is 1 (Rosewell, 1993). Uncultivated natural forest, and grasslands, roads and river banks or contour-graded systems, which usually reduce sheet and rill erosion, will also have a P-Factor of 1 (Goldman *et al.*, 1986; Schulze, 1989; Rosewell, 1993; University of Zululand, 2001, 2003).

The P-Factor of the study area was estimated as 1 because:

1. The area was mostly covered by pine forest before the bushfire event on 18 January, 2003;
2. At the time of the fieldwork, the area was covered by debris from the pine plantation and grass, and the recovery management and replanting increased the ground cover;
3. The average slope of the area is about 9.4 percent, that is, close to the range of minimum soil loss (3 –8%);
4. The area of interest is forest roads, and the P value for roads is generally 1.

A P-Factor grid layer with a value of 1 was created and then used as one of six factors of RUSLE for estimating soil loss in the study area, particularly from the forest roads.

5.2.5 Average Annual Soil Loss and Erosion Risk

The output of the RUSLE model is a prediction of average annual soil loss per unit area ($t.ha^{-1}.y^{-1}$). This output is a grid GIS layer showing the soil loss distribution value per unit area (20 * 20 metre pixels). It was derived by applying the model using ArcGIS. Figures 5.2 and 5.3 illustrate the distribution of the probability of soil loss risk resulting from implementing RUSLE using GIS across the study area and forest roads.

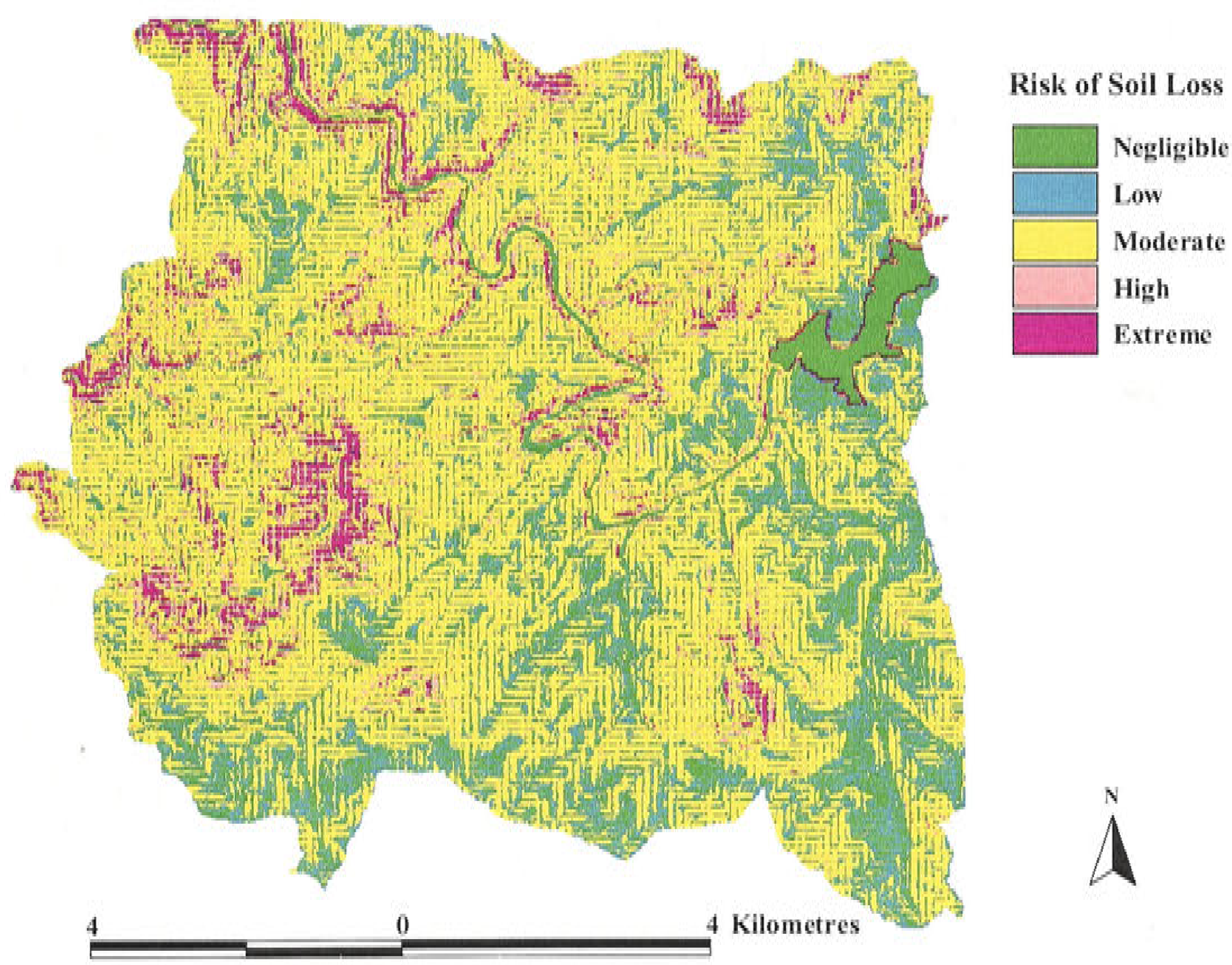


Figure 5.2. Soil loss and probability of erosion risk for the study area

Table 5.10. Parameters for estimated annual soil loss ($t.ha^{-1}.y^{-1}$) for the study area

Area (ha)	Minimum Value	Maximum Value	Mean Value	Standard Deviation	Range
10477	0	124	7	8	124

Table 5.10 shows the minimum, maximum and mean values of predicted soil loss in the study area to be about 0, 124 and 7 tonnes per hectare per year, respectively. The highest level of expected soil loss occurred on the ridge above the Molonglo River and on the sides

of Mount Stromlo, where the values of the slope gradient and slope length are higher than for other areas.

The risk of soil loss of the study area and forest roads was ranked using the processes explained in Chapter 4, section 4.8. The risk-ranking scores were first estimated and the score associated with each cell in the risk matrix was then used to evaluate the level of risk, from extreme, high, moderate to low/negligible. The probability of soil loss from the site and the erosion rate are expected be low to very low when the slope gradient is between 0 – 8 degrees (Forestry Commission of Tasmania, 1993; Ryan *et al.*, 1998; Australian Government, 1992, 2000). For example, the likelihood of losing soil from the landscape and forest roads located in a flat area would be 'rare' (level 1: see Table 4.6) and 'unlikely' (level 2). In this situation, the potential soil loss rate would be very low because of low level of water movement due to a lack of the energy needed to transport soil particles associated with a small slope value. The consequences, therefore would be 'insignificant' (level 1: see Table 4.7) and 'minor' (level 2). The risk ranking scores associated with these levels of likelihood and consequences would be between 1 and 4, and the risk levels associated with these scores are 'negligible' and 'low', respectively. The field investigation confirmed that there was no evidence of erosion across the landscape or of rill or gully erosion on the surface of the roads and at the outlets of the drainage structures, for these categories. Furthermore, the roads built on the flat areas (in this case study area, about 40% of the roads) have no substantial cut and fill batters, and where they do exist the height and slope values of cut and fill batters are very low. In this situation, the contributions of erosion from cut and fill batters to the total possible erosion rate from roads, therefore, would be negligible.

In hillslope conditions, there is a higher probability of having a high rate of soil loss and gully formation compared with the lower slope and flat areas (British Columbia Environment, 1995a). Gully formation would probably occur on the hillslope, and on the surface of the roads and at the outlet of drainage structures, when the slope gradient exceeds 25% and where the ground cover is low (British Columbia Environment, 1995a; Ryan, 1998). The greater the slope, the higher is the velocity of the flow of the run-off across the landscape and on the road surface, which may cause high erosion rates and gully formation. As described in Chapters 2 and 4, the likelihood of the erosion occurrence on steep terrain ranges from 'likely' to 'almost certain', depending on the magnitude of the slope value, site conditions, and damage to road and ground covers. The consequences of soil loss for this condition range from 'moderate' to 'catastrophic', depending on the magnitude of the slope gradient that provides energy for soil particle movement. The ranking scores for these categories for the study area and its roads range from 9 – 16, and the associated risk would be 'high' and 'extreme', respectively. The soil loss rates for these categories are 15 – 25 and >25 tonnes/ha/yr, respectively. Van Vliet *et al.* (2002) used a 'risk of water erosion indicator' (that is, >22 tonnes/ha/yr for high to very high risk) to identify areas at risk of significant water erosion. The ranking score for 'moderate' risk is estimated at 6 (Tables 5.11 and 5.13), using the same procedures described above.

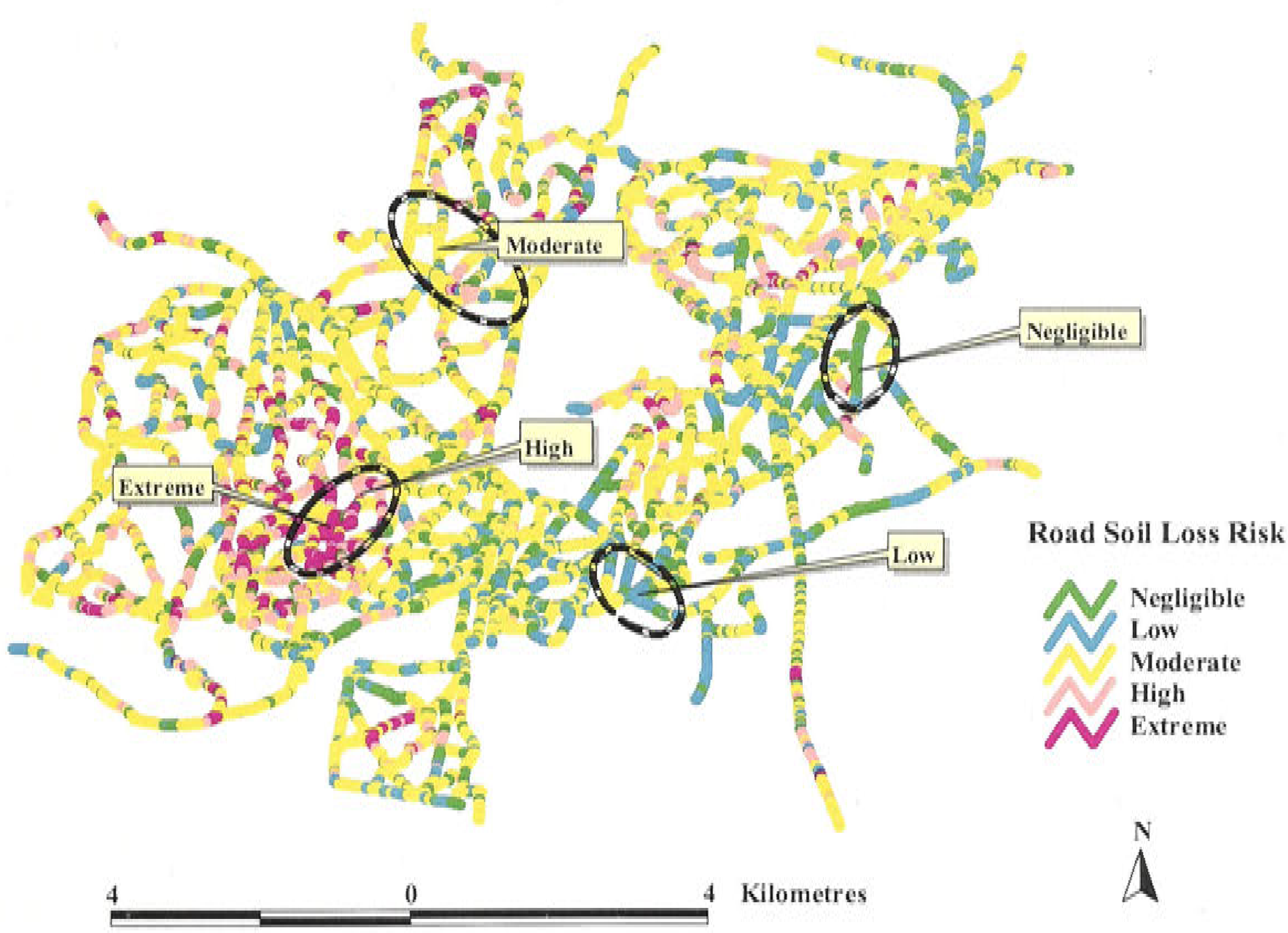


Figure 5.3. Soil loss and probability of erosion risk of forest roads of the study area

As summarised in Table 5.11, there is a predicted risk of 'moderate' soil loss for around 42% of the study area. The next largest area (31%) is that ranked as having 'low' soil loss. Sixteen percent of the study area was ranked as having negligible soil loss; this was located in the lowest slope or flat area (Figure 5.2 and Table 5.11). Eleven percent (1196 ha) of the study area is at risk of 'high' and 'extreme' risk of soil loss.

Table 5.11. Summary of the risk of soil loss across the study area

Risk of Soil Loss ($t.ha^{-1}.y^{-1}$)	Negligible (<1)	Low (1.01 – 3)	Moderate (3.01 – 15)	High (15.01 – 25)	Extreme (>25)
Area (ha)	1669	3218	4394	781	415
Percent	16	31	42	7	4

The majority of the study area (53%) is assessed as having moderate to extreme risk of soil loss (Table 5.11).

Table 5.12. Summary parameters ($t.ha^{-1}.y^{-1}$) for soil loss from the forest roads of the study area

Road Length (km)	Minimum Value	Maximum Value	Mean Value	Standard Deviation	Range
307	0.2	84	9	9	84

Table 5.13. Summary of the risk of soil loss from Forest Roads across the study area

Risk of Soil Loss ($t.ha^{-1}.y^{-1}$)	Negligible (<1)	Low (1.01 – 3)	Moderate (3.01 – 15)	High (15.01 – 25)	Extreme (>25)
Road Length (km)	38	75	150	30	14
Percent	12	24	49	10	5

Figure 5.3 illustrates and Tables 5.12 and 5.13 summarise the distribution of the soil loss values and risk of soil erosion categories for forest roads in the study area. As shown in Table 5.12, the minimum, maximum and mean values of possible soil loss of the forest road are 0.2, 84, and 9 tonnes per hectare per year, respectively. The maximum value of soil loss from the forest roads is nearly 40 tonnes per hectare per year less than the maximum value for the entire study area, but the mean value is 2 tonnes per hectare per year higher than that of the entire study area (Tables 5.10 and 5.12).

About 12 percent (37 km) of the forest roads of the study area are ranked as having 'negligible' soil loss, and 13 percent (39 km) are predicted to have 'low' risk of soil loss (Table 5.13). More than half (59 percent) of the forest roads are predicted to have 'moderate' rates of soil loss. 'High' or 'extreme' risk of soil loss (15 to more than 25 $t.ha^{-1}.y^{-1}$) are predicted for 16 percent (51 km) of the forest roads. These roads are mostly located in high slope areas, such as around Mount Stromlo. As a result, most of the forest roads (75 percent) of the study area are ranked as having 'moderate' to 'extreme' risk of soil loss.

5.3 Summary and Conclusions

The RUSLE is well established as a method for determining relative susceptibility to soil loss over a land area. Values can be calculated and mapped using GIS-based techniques for evaluation and planning in both forested and non-forested catchments. The GIS-Based model of RUSLE is available in the IDRISI modelling module, and grid commands are available in the ArcGIS software. The use of ArcGIS was preferred in this study. The factors involved in the model were individually calculated and/or estimated using different GIS approaches in order to obtain a realistic result. This application was made over an area of about 10,000 ha that included about 307 km of forest roads. The result is an estimate of relative potential soil loss and soil erosion, however it is not an estimate of sediment delivery downstream by runoff. The risk levels (low to extreme) shown in the maps were used to create an integrated final risk map in the final stage of evaluation (Chapter 8). The soil loss risk map of the study area was used as one of the components in the final risk evaluation process.

The risk ranking and classification of soil erosion in both the landscape of study area and its forest roads were consistent with the results of the field observation. For example, in areas where 'extreme' and 'high' erosion risk were indicated by the model, evidence of considerable erosion, such as the presence of rills and gullies, was found on the surface of the roads or at the outlets of the road drainage structures.

Chapter 6
Results and Discussion 2: Digital Terrain Modelling and Development of Rill and Gully Occurrence Risk Models

6.1 Introduction

Digital Terrain Modelling (DTM) and Digital Terrain Analysis (DTA) were developed almost 20 years ago. They are methods based on GIS technology used to model environmental effects. DTM, a set of techniques used to derive or present a Digital Elevation Model (DEM), is a powerful tool in GIS analysis and visualization (Hengl *et al.*, 2003). A DEM is a digital representation of part of the earth's surface (see also Chapter 2). DTA is the process of quantitatively describing terrain (Hengl *et al.*, 2003). DTM and DTA are generally used for derivation of terrain parameters and their application (Moore and Wilson, 1992; Hengl *et al.*, 2003). Although using the terrain attributes and analysis in environmental management systems is not new, digitisation and analysis of terrain attributes have recently improved, following improvements in computer technology and the ability to compute environmental phenomena. Current DTM and DTA approaches derive principally from the efforts of Moore and his colleagues (for example, Moore and Burch, 1986; Moore and Nieber, 1989; Moore and Foster, 1990; Moore and Hutchinson, 1991; Moore and Wilson, 1992) in the second half of the 1980s and the beginning of the 1990s.

Terrain attributes play important roles in forest road and hydrology management systems. Some terrain attributes are key factors in managing and controlling the effects of forest roads on the environment. For example, Moore *et al.* (1986, 1991), Croke *et al.* (1999, 2001), Pallaris (2000), Croke and Mockler (2001), Hairsine *et al.* (2002) and Takken *et al.* (2005) have pointed to certain terrain attributes – such as slope gradient, slope length, aspect, road contribution length and area, specific catchment area, upslope contribution area and slope position – as being the most important factors influencing forest road and timber harvesting impacts on soil and water.

In this chapter, the DTM used in the study is described and the calculation procedures, processes and results of derivation of each terrain attribute are explained. The data sources and data collected from the field, the road database developed from the terrain attributes values and field data, and variables used for analysis are then discussed. The effects of each factor – the independent variables – on the dependent variable – rill and gully erosion occurrence – were tested using logistic regression and ANOVA. The results of these analyses are presented as separate models predicting rill and gully occurrence on the road surface and at the outlets of road drainage structures, and road-to-stream connectivity. The quality of the models derived from the development data set was tested using the Hosmer-Lemeshow goodness-of-fit test, R squared, residual plots, and relative operating characteristics (ROC) curve. These models were then tested and validated using the validation data set.

6.2 Analysing Digital Elevation Models (DEMs) Using Relief Analysis Within ArcGIS and IDRISI

Using cell-based Digital Elevation Models is the most common method used for calculating data relating to the shape of the earth's surface. DEM is used as the input layer in GIS-based processes to quantify the characteristics of the land surface and for extracting relevant information for land management (Moore *et al.*, 1991; Wilson and Gallant, 2000; Pallaris, 2000).

A DEM with 20 metres resolution (CRES, 2003) was used in this study for analysing and creating the terrain attribute layers. Using ArcGIS, the DEM layer was first subjected to 'fill sink' and 'pit removal' procedures to create a depressionless DEM. This step is necessary in DEM and DTA analysis to extract the relevant data and information as accurately as possible. For example, cells that do not appear to drain anywhere become a problem when using DEM analysis for tasks such as the building of a drainage network. Mark (1998), Moore and Hutchinson (1991), Moore *et al.* (1993) and Pallaris (2000) argued that most errors in DEMs and DTM processes come from either sinks or peaks. A sink is defined as an area that will be surrounded by higher elevation values; this is also known as a pit or depression area.

The primary terrain attributes of the study area – slope, aspect, curvatures (profile, plan and tangential), flow direction and flow accumulation – were calculated from directional derivatives of a topographic surface using the DEM. Secondary relief parameters – Compound Topographic Index (CTI) and Stream Power Index (SPI) – were computed using ArcInfo. Relief analysis of the DEM was applied using the DEM analysis processes including second order finite differences and fitting a bivariate interpolation function, as explained in Moore *et al.* (1993), Pallaris (2000), Wilson and Gallant (2001) and Reuter (2003).

In this chapter, the process of calculating a number of derived indices – slope, slope position, aspect, curvatures, CTI and SPI – is described. Flow direction, flow accumulation, flow pathway, USCA, road-to-stream hydrologic distance, and watershed delineation processes are described in Chapter 7. These indices were based on published work that suggested they could provide an explanation for the likelihood of stream sedimentation. Each index was tested to determine its suitability as an explanatory variable for the risk of stream sedimentation.

6.2.1 Slope

Slope and aspect values are known as a first derivative from the DEM (Gallant and Wilson, 2000). The slope gradient of the study area was calculated using the grid commands of ArcGIS 9. The procedure used for calculating the slope of the study area was based on the concepts and formulae developed by Burrough (1986), Burrough and McDonnell (2000), Gallant and Wilson (2000) and Eastman (2002). Table 6.1 summarises the calculated slope for the study area.

Table 6.1. Parameters of slope (in degree and percent) of the study area

Area (ha)	Unit	Minimum Value	Maximum Value	Mean Value	Standard Deviation	Range
10477	Degree	0	43	5	4	43
	Percent	0	93	9	8	93

Terrain stability mapping based on the infinite plane slope stability model of hydrology (Pack *et al.*, 1998) requires stability classes to be mapped in order to easily identify regions and segments of roads that need more detailed assessment. Stability Indices (SI) of the study area and forest roads were mapped using GIS and the SINMAP (Stability Index Mapping) model developed by Pack *et al.* (1998). Although the SI generally refers to mass wasting and landslide hazards, the map and results of SI analysis can also be used to indicate the segments of roads which are more likely to have sheet (rill and gully) erosion due to table drains being blocked by cut slope failure. The reason for carrying out the SI analysis and mapping was to determine whether there was any correlation between slope failure and distribution of sheet erosion on the surface of the roads or at the outlets of drain structures.

The results of the stability assessment showed that nearly 90% of the study area and 80% of the forest roads were stable or moderately stable. About 90% of the study area and 79% of forest roads were recognised as having 'negligible' risk level. Less than 5% of the study area and around 11% of forest road network were associated with 'moderate', 'high' or 'extreme' risk. The western parts of the SFMA around Mt. Stromlo and around the Molonglo River were the areas found to be most at risk of instability. Data and information related to slope failure were gathered during the field survey in order to validate the results of this analysis. As the roads were built more than 30 years ago, the cut batters have become stable over time, and there were no major slope failures found during field investigation. Thus, although the Slope Index map shows some areas with a high or extreme risk of slope failure occurrence, no substantial slope failure problems were found in Stromlo Forest.

6.2.2 Landform Classification and Slope Position Analysis

As described in Chapter 4, section 4.4.2, the landform classification was carried out using a concavity/ convexity index which calculated the following landform index introduced by McNab (1989, 1991, 1993), Bolstad (1998) and Jeffrey (2002). A program written in Arc Macro Language (AML), originally from Jeffrey (2002), was updated and adapted for this study. This AML, and ArcGIS Grid and Arc commands, were used for calculating the landform index.

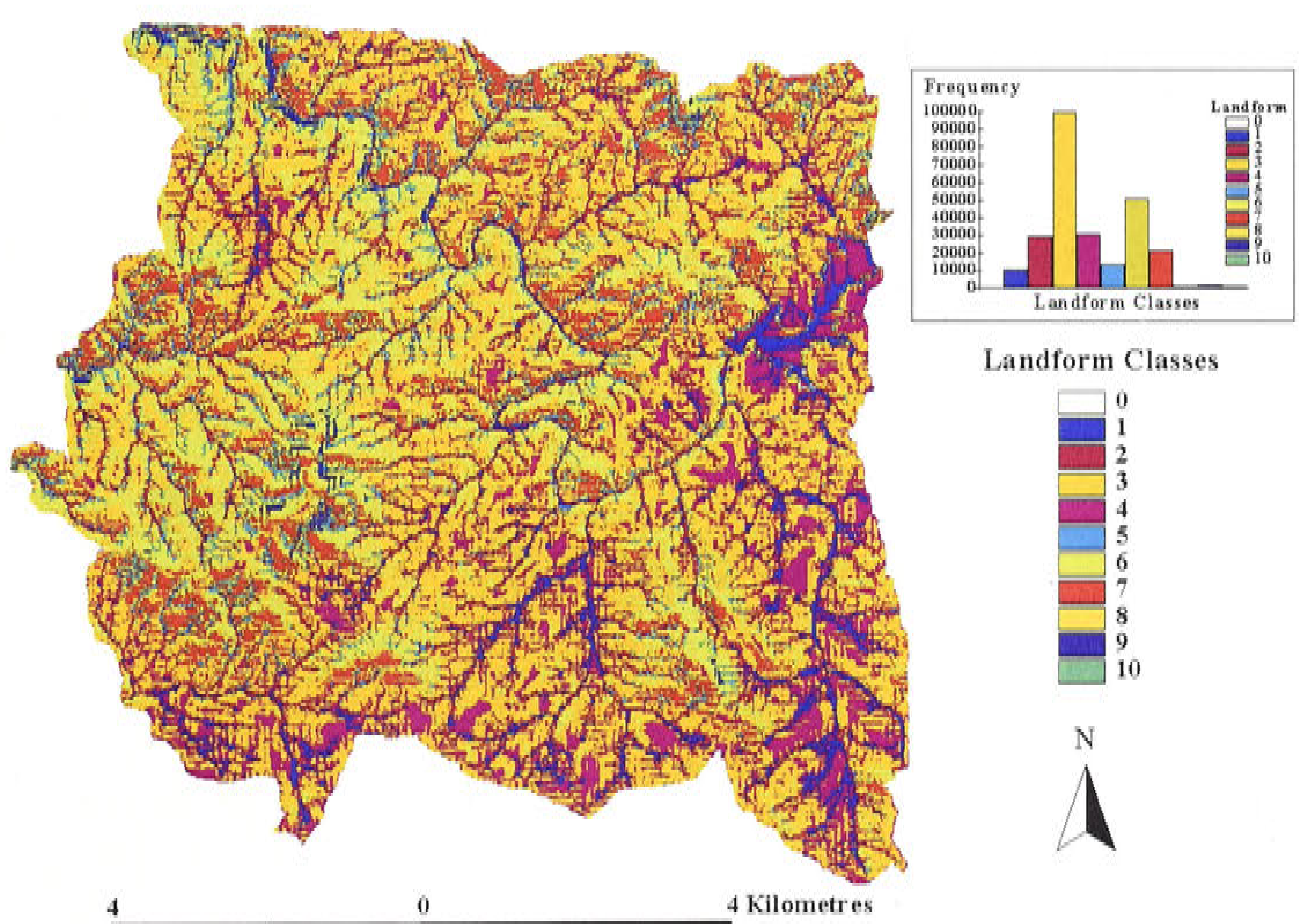


Figure 6.1. Landform classification of the study area

Figure 6.1 illustrates the landform classification of the study area. As can be seen from the figure and Table 6.2, gentle ridges and sloping hilly area (class 3) comprised more than 38% of the study area, and comprised the majority of the 10 landform classes. Of the overall landform classification of the study area summarised in Table 6.2, more than 65% was classified as having low, gentle and moderate slopes (classes 1- 4); less than 35% of the area is located on steep slopes.

Table 6.2. Summary of landform classification of the study area

Classes	Name	Area	
		ha	%
0	-	1.4	0.01
1	Valley flats	423	4.04
2	Toe slopes, bottoms	1183	11.3
3	Gently sloping ridges and hills	3987	38.1
4	Nearly level plateaus or terraces	1237	11.8
5	Very moist steep slopes	551	5.3
6	Moderately moist steep slopes	2036	19.4
7	Moderately dry slopes	871	8.3
8	Very dry steep slopes	47	0.5
9	Cool aspect cliffs, scarps, cirques, canyons	82	0.8
10	Hot aspect cliffs, scarps, cirques, canyons	58	0.6

Slope position of the study area and the forest roads was calculated using the procedures described in Chapter 4, section 4.4.2. An AML from the USDA, originally written by Hatfield (2003), was adapted for the study area. A DEM layer (20 m resolution) and forest road layer of the study area were used as inputs for running the model. Figure 6.2 illustrates the slope position classes of the study area. As can be seen from the figure, and Table 6.3, more than 50% of the study area is categorised as having 'midslope' (class 2) position.

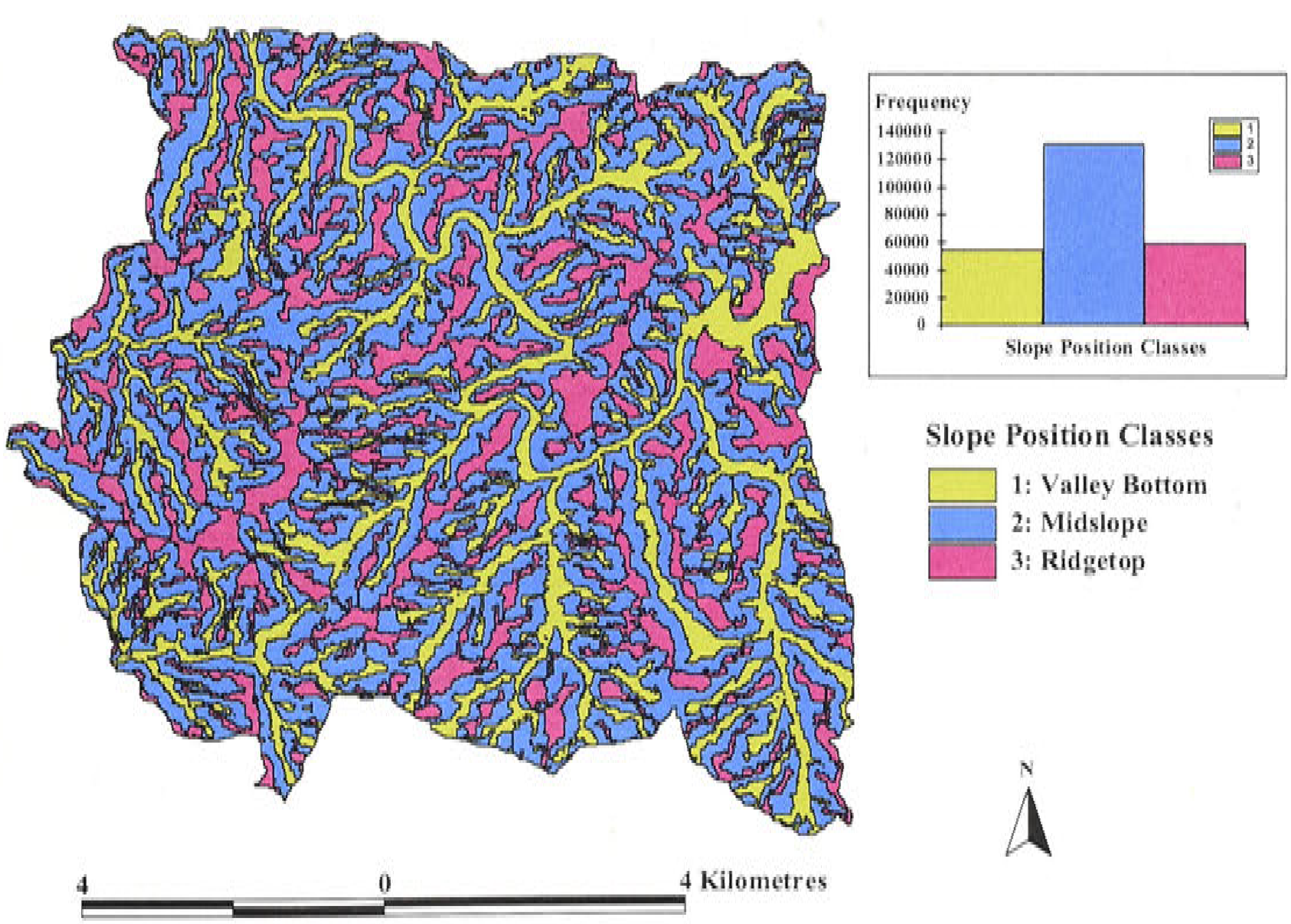


Figure 6.2. Slope position classes of the study area

Table 6.3. Summary of slope position of the study area

Slope position		Area	
Classes	Name of Class	ha	%
1	Valley Bottom	2334.28	22.28
2	Midslope	5596.81	53.42
3	Ridgetop	2545.91	24.30
-	Total	10477	100

Table 6.3 summarises the slope position classification of the study area. More than 22% of the study area is classified as 'valley bottom', while about 53% and 24% are 'midslope' and 'ridgetop', respectively.

6.2.3 Aspect

Aspect shows the direction and the maximum rate of change of the slope value. Generally, areas of different slopes differ in their alignment to the sun and each area can also have a different wetness index. The aspect of the study area is calculated based on Formula 2.4 (Chapter 2) using ArcGIS and ArcView. Each cell is generally assigned a unique aspect regarding its slope value using a standard azimuth designation starting from north. The distribution of aspect for forest roads in the study area is given in Table 6.4.

Table 6.4. Aspect class distribution for the forest roads

Aspect	Road Length (km)	Percent
North	38	12
Northeast	36	12
East	51	17
Southeast	39	13
South	35	11
Southwest	27	9
West	36	12
Northwest	44	14
Flat	3	1

6.2.4 Curvatures

Curvature attributes are generally based on a second derivation from the DEM, which measures the rate at which the aspect and slope change. The curvatures of the study area are calculated using ArcInfo and equations 2.8 to 2.10, described in Chapter 2. The values of curvature (profile, plan and tangential) show the change in orientation resulting from travelling 1 metre (the units are radians per metre) along the respective line (Gallant and Wilson, 2000). Profile, plan and tangential curvature layers were used for characterizing and studying the flow, flow velocity, sediment transport capacity, convergence and divergence of water flow across the study area. The results are discussed in Chapter 7.

Table 6.5. Parameters of profile curvature for the study area

Area (ha)	Minimum Value	Maximum Value	Mean Value	Standard Deviation	Range
10477	-6	6.3	0.33	0.9	11.96

The negative values of profile curvature are related to a convex flow profile on the upper slope, or a slope that increases downhill (Table 6.5). The positive values are associated with concave profiles on lower slopes or slopes decreasing downhill (see also Chapter 2, section 2.4.3).

Table 6.6 shows the distribution of plan curvature value for the study area. The plan curvature values of the area are distributed from –7 to 7.5. The mean and standard deviation values are 0.7 and 1, respectively.

Table 6.6. Parameters of plan curvature for the study area

Area (ha)	Minimum Value	Maximum Value	Mean Value	Standard Deviation	Range
10477	-7	7.5	0.7	0.99	14.5

Table 6.7 summarises the distribution of the values of the profile and plan curvatures in the study area. About 82% (8690 ha) and 65% (6872 ha) of the study area are categorised as

having profile curvature and plan curvature values of less than 1, respectively. As shown in Table 6.7, about 41% (4314 ha) of the study area is recognized as having a convex flow profile area and 59% (6163 ha) of the area is categorised as having a concave flow profile.

Table 6.7. Summary of distribution of the profile and plan curvatures in the study area

Curvature Class Ranges	Number of pixels		Area in hectares		Percent	
	Profile	Plan	Profile	Plan	Profile	Plan
-7 - -3	164	148	6.6	5.9	0.06	0.06
-3 - <0	107691	83539	4307.6	3341.6	41.1	31.9
0 - 1	107076	88260	4283	3530.4	40.9	33.7
1 - 4	46951	89909	1878	3596.4	17.9	34.3
4 – 7.5	43	69	1.7	2.8	0.02	0.03

Tables 6.8 and 6.9 show the distribution and statistical summary, respectively, of the tangential curvature of the study area. The tangential curvature of the study area is calculated by multiplying the plan curvature by the sine of the slope angle. As the tangential value does not take on extremely large values when the slope value is small, it is more reliable than the plan curvature for assessing the flow convergence and divergence (Mitasova and Hofierka, 1993; Gallant and Wilson, 2000). As can be seen from Table 6.8, the minimum, maximum and mean values of the tangential curvature are -1.5, 3.6 and 0.03, respectively. Table 6.9 shows that most of the tangential curvature values of the study area fall within the range -1.5 - 1, covering approximately 59% of the area. About 47% (4879 ha) of the area is categorized as having a tangential curvature value of less than 0 while more than 52% (5479 ha) of the area is given a value of between 0 and 1. Plan and tangential curvature layers are used for creating the landform classification and slope positioning layers of the study area and forest roads by considering differences between ridges, valley bottom, and hillslopes.

Table 6.8. Parameters of tangential curvature for the study area

Area (ha)	Minimum Value	Maximum Value	Mean Value	Standard Deviation	Range
10477	-1.5	3.6	0.03	2.3	5.05

Table 6.9. Summary of distribution of the values of the tangential curvature in the study area

Tangential Curvature Classes	Number of pixels	Area (ha)	Percent
-1.5 - -0.5	262	10.5	0.1
-0.5 - 0	121714	4868.6	46.5
0 - 1	136971	5478.8	52.3
1 – 2.5	2940	117.6	1.1
2.5 – 3.6	38	1.5	0.01

Figure 6.3 illustrates the total curvature values of the study area. Total curvature is shown as the surface curvature measurement. According to Gallant and Wilson (2000), the total curvature is not the curvature of a line across the surface in some direction, but the measure of the curve of the surface which can be either positive or negative and/or zero.

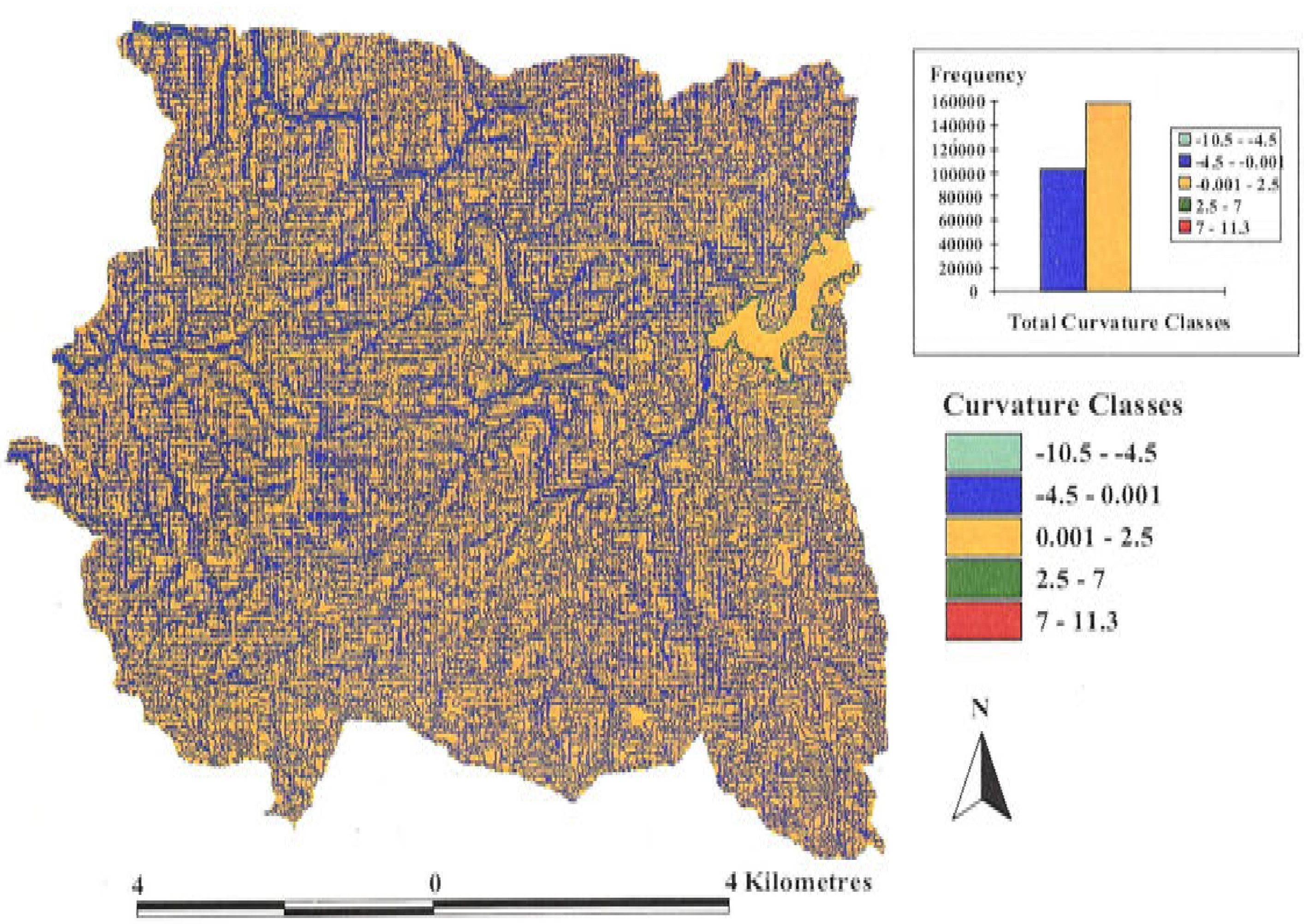


Figure 6.3. Total curvature layer for the study area

The histogram analysis of the total curvature layer provides a statistical summary for the area, as shown in Table 6.10. After creating the total curvature layer, the resulting image was reclassified into 5 broad curvature classes (Table 6.11). The result shows that around 39% (4118 ha) of the study area is classified as having negative curvature values. Also, as can be seen in Table 6.11, most of the area (more than 60%) has between 0 and 2.5 curvature values. Other curvature classes only comprise relatively small percentages, less than 1%, of the study area.

Table 6.10. Parameters of tangential curvature for the study area

Area (ha)	Minimum Value	Maximum Value	Mean Value	Standard Deviation	Range
10477	-10.5	11.3	0.42	1.05	21.75

Table 6.11. Summary of distribution of the values for the tangential curvature in the study area

Total Curvature Classes	Number of pixels	Area (ha)	Percent
-10.5 - -4.5	161	6.4	0.06
-4.5 – 0.001	102953	4118.1	39.3
0 – 2.5	158319	6332.8	60.4
2.5 – 7	464	18.6	0.2
7 – 11.3	28	1.1	0.01

6.2.5 Compound Topographic Index (CTI)

CTI (also called Topographic Wetness Index (TWI)), as described in Moore *et al.* (1993), is an index of moisture retention based on basin size or specific catchment area and slope (see also Chapter 2, section 2.4.3). CTI is used to predict and characterise the spatial distribution of the surface saturation zone and soil water content in the landscape. The CTI value is also used to predict overland flow or the propensity of overland flow to carry sediment at catchment scale. CTI is considered as one of the most important variables influencing the impacts of forest road on the soil and water (Moore *et al.*, 1993). Figure 6.4 shows the CTI layer for the study area. The CTI values of the area are mostly distributed around the mean value (7), as summarised in Tables 6.12 and 6.13.

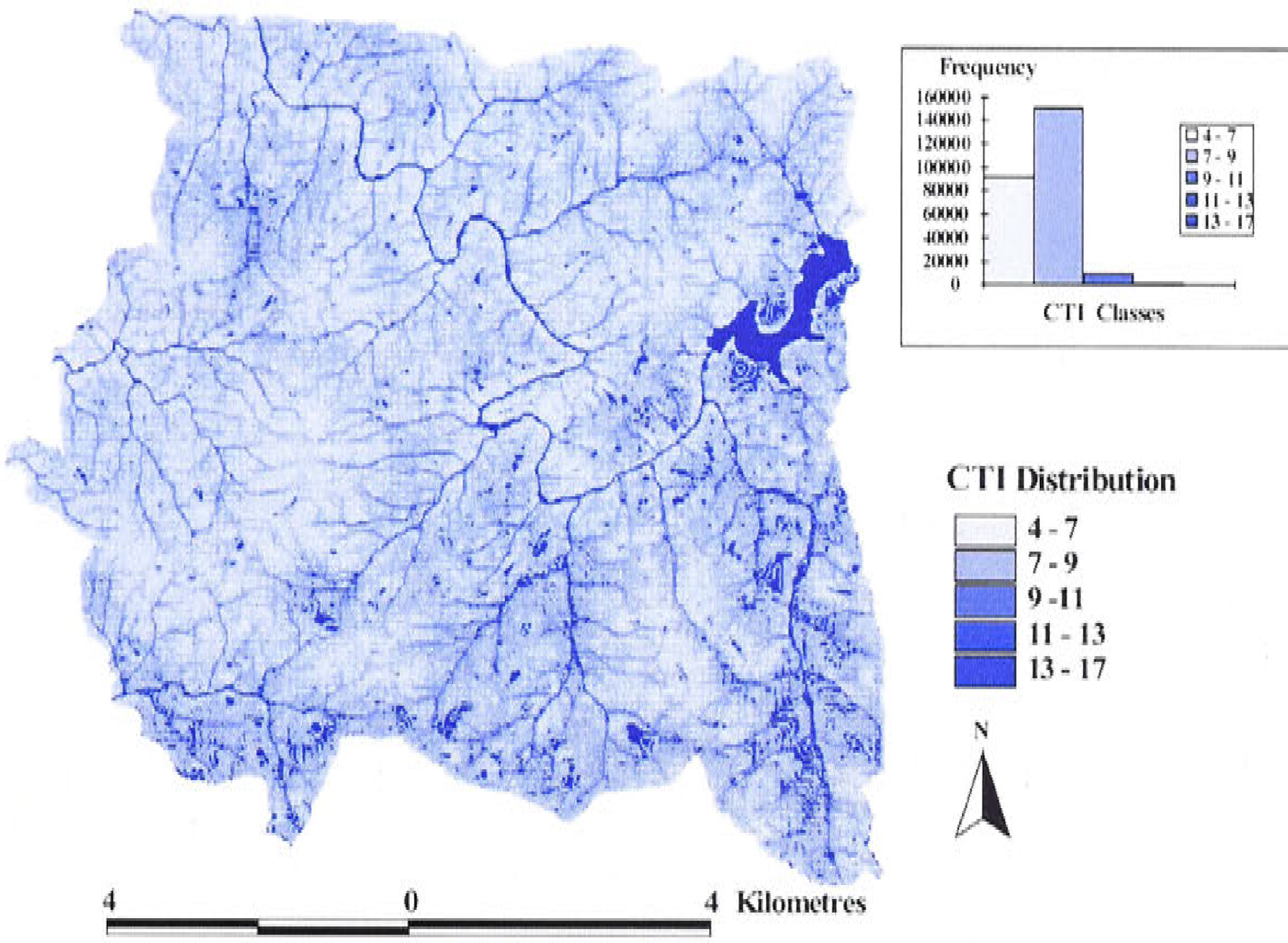


Figure 6.4. Compound Topographic Index (CTI) layer for the study area

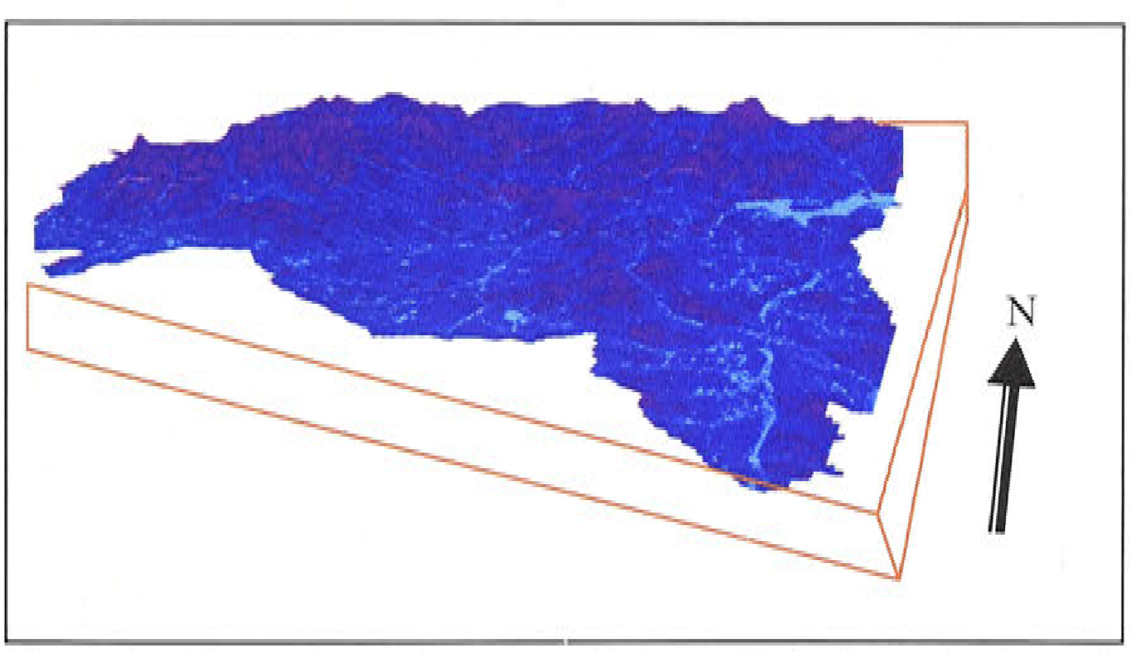


Figure 6.5. Three-dimensional view of Wetness Index layer for the study area draped over DEM

An area with high values for the wetness index is most likely to become saturated quickly during rain, especially during a heavy storm. Therefore, overland flow and the contribution of surface runoff to adjacent streams are logical results of quick saturation. Also, if the volume of the runoff is high and there is a connection between the source of the sediment (for example, forest roads) and the streams, deterioration of stream water quality is possible. The three-dimensional layer of CTI (Figure 6.5) clearly illustrates this possibility.

The dark and bright blue colours illustrate high values of the Wetness Index where there will be overland flow and, therefore, where the topsoil is most likely to be detached, resulting in erosion and possible sediment delivery to the streams.

Table 6.12. Parameters of CTI values for the study area

Area (ha)	Minimum Value	Maximum Value	Mean Value	Standard Deviation	Range
10477	4.7	16.9	7.4	1.05	12.2

Table 6.13. Summary of the CTI values for the study area

CTI Classes	Number of pixels	Area (ha)	Percent
1: 4 - 7	92244	3689.8	35.2
2: 7 - 9	150776	6031	57.6
3: 9 - 11	11940	477.6	4.6
4: 11 - 13	5051	202	1.9
5: 13 - 17	1914	76.6	0.7

Tables 6.12 and 6.13 show that the lowest CTI class (CTI value <7), with the least possibility of being subjected to the overland flow, comprises more than 35% (3690 ha) of the study area. Class 2 (7 – 9) is the dominant value, being distributed over about 58% of the study area. CTI classes with higher values are distributed over about 7% (about 755 ha) of the study area; these have a greater probability of contributing to overland flow and surface runoff.

6.2.6 Stream Power Index (SPI)

The Stream Power Index is a measure of the erosive power of overland flow. According to Moore and Burch (1986b), Gallant and Wilson (2000) and Pallaris (2000), the unit stream power theory provides the basic rationale for understanding overland flow generation and behaviour. It also shows the potential energy available at any pixel or point causing sheet erosion and carrying sediment. The ratio of SPI increases with an increase in slope angle and the size of a specific catchment area (Pallaris, 1999).

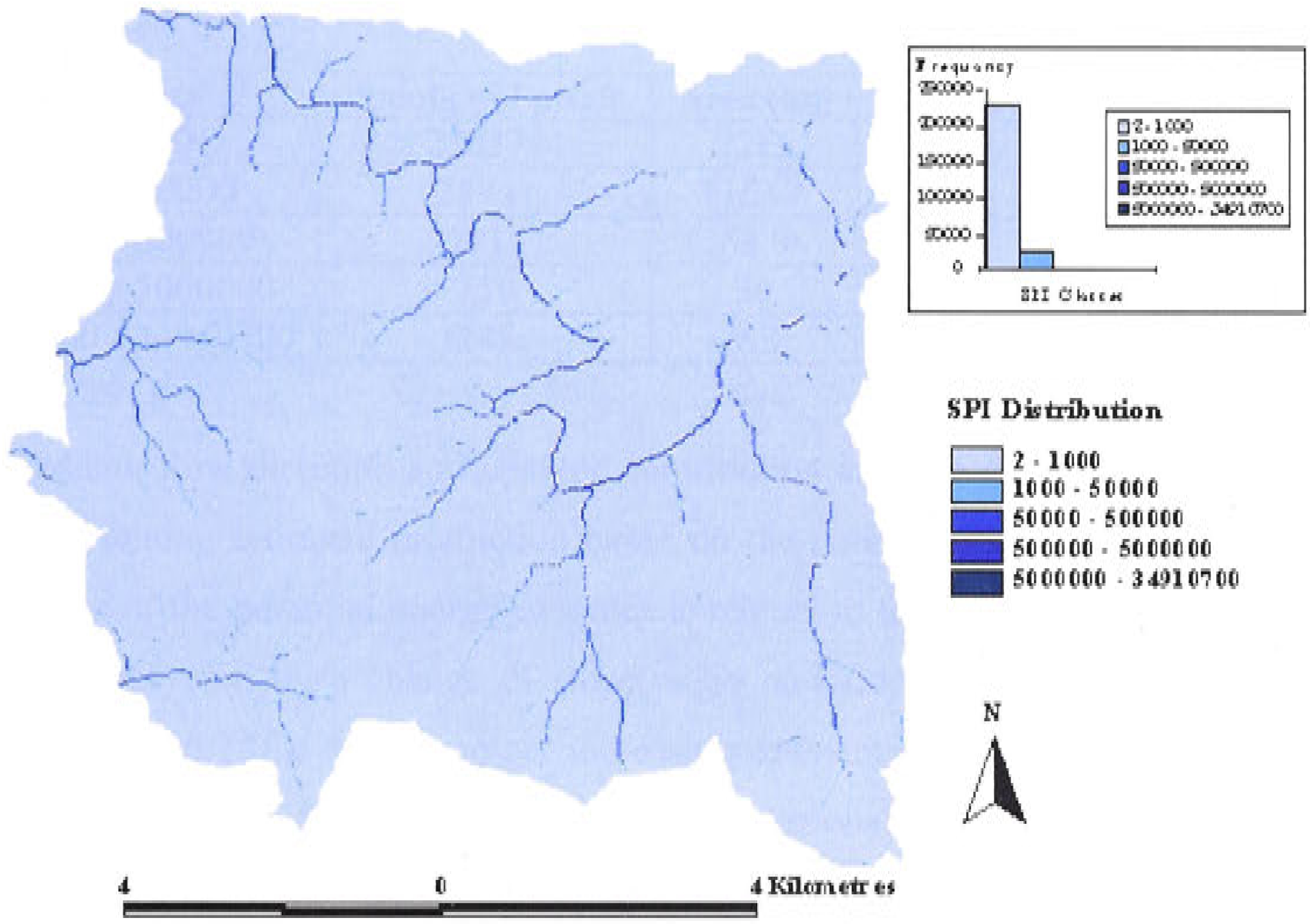


Figure 6.6. Stream Power Index (SPI) layer for the study area

The SPI of the study area was calculated using the background information and formulae described in Chapter 2. As shown in Figure 6.6, most of the SPI values are distributed in class 1, between 2- 1000. The minimum, maximum and mean SPI values of the study area are 2, 34910700, and 12381, respectively (Table 6.14). As can be seen from Table 6.15, about 88% (9215 ha) of the study area constitutes class 1 (2 – 1000) of SPI values and about 1% of the area is associated with a high value of the SPI (more than 50,000).

Table 6.14. Parameters of SPI values for the study area

Area (ha)	Minimum Value	Maximum Value	Mean Value	Standard Deviation	Range
10477	2	34910700	12381	270894	34910698

Table 6.15. Summary of the SPI values for the study area

SPI Classes	Number of pixels	Area (ha)	Percent
1: 2 - 1000	230374	9215	88
2: 1000 - 50000	28841	1153.6	11
3: 50000 - 500000	1715	68.6	0.7
4: 500000 - 5000000	750	30	0.3
5: 5000000 - 34910700	245	9.8	0.1

Slope gradient, flow direction and upslope contribution area are the three most important factors determining sediment production based on the potential energy of the runoff. The driving force of the potential energy of water is related to the speed and amount of water that will be provided by a change of slope angle and slope length (Pallaris, 2000). As shown in Figure 6.7, the stream power increases exponentially with an increase in slope gradient. The volume of discharge is directly proportional to the upstream contributing (accumulation) area.

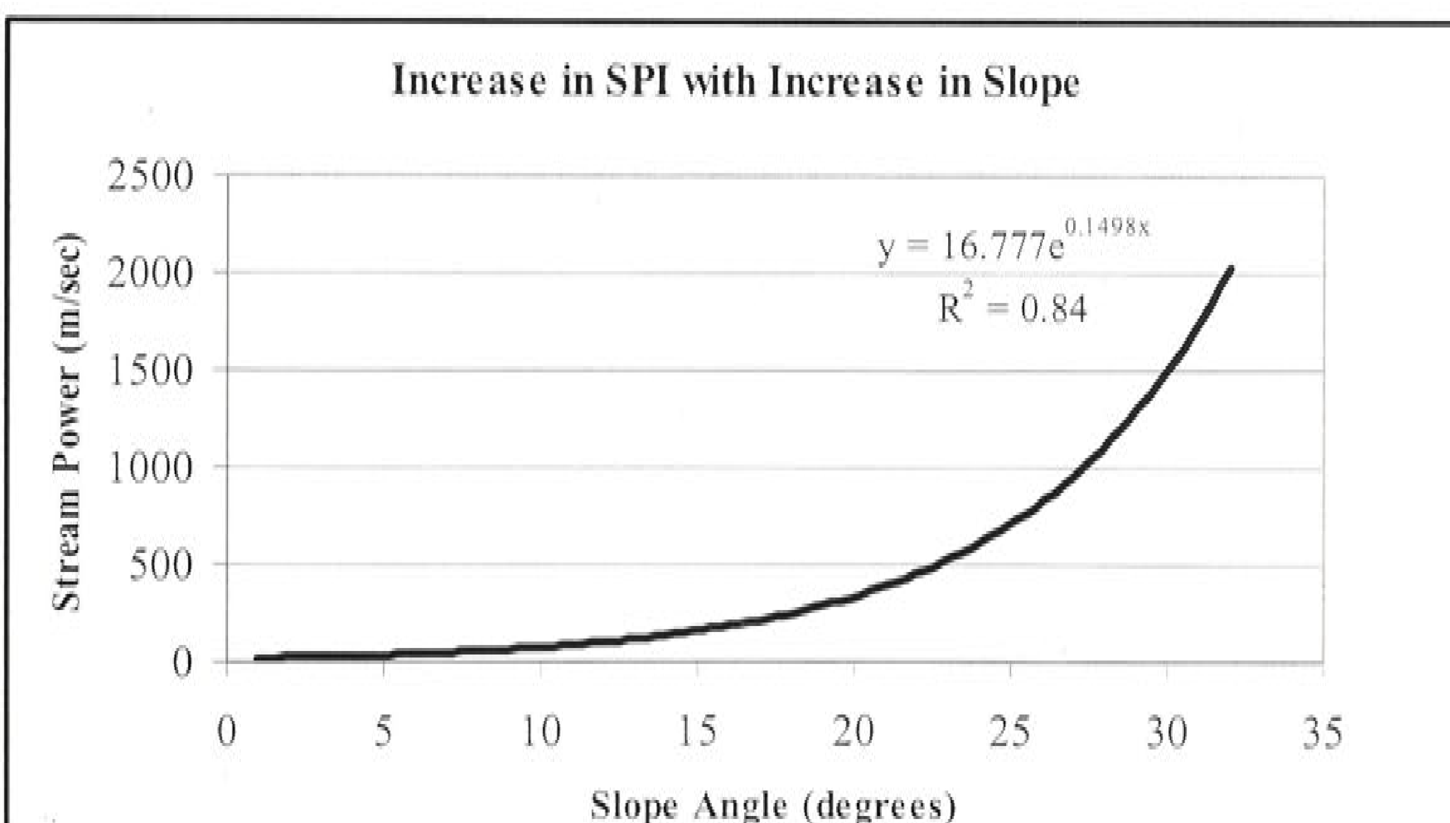


Figure 6.7. Relationship between Stream Power (discharge) and slope

Source: Adapted from Pallaris (1999)

6.3 Data Sources

Data used in this study are from two sources: data collected in the field, and terrain attribute data from DTM. As described in Chapter 4, data and information about forest road characteristics were collected from Stromlo Forest. Field data were gathered over three fieldwork periods (September – December 2001, May – December 2002, and May 2003 - June 2004) which were widely spaced due to the bushfire events in 2001 and 2003. The sample data actually used in this study for the analysis phase were all from the last period of fieldwork, which took place after the 2003 bushfire. Terrain attribute data were derived from the DEM of the study area using terrain analysis, as described in section 6.2 in this chapter, section 2.4, Chapter 2, and section 4.4, Chapter 4.

6.3.1 Preparation of the Field Data

The position accuracy for uncorrected GPS data (stand-alone GPS) is about 100 metres. The data therefore needed to be corrected using the Reliance software supplied with the instrument. The software uses a differential correction to obtain highly accurate positions from the data collected (Magellan Corporation, 1998).

The results of corrections using this differential process showed that the errors of feature positioning were mostly less than 20 cm, especially if data had been gathered with high satellite availability. All field-recorded data were transferred from DGPS into the Reliance software and were then processed by the software in order to correct and prepare the data for conversion into a GIS format data layer. The software tested the accuracy of each data point, and data that had a very high error could not be processed and were removed from the data sets. Collection was repeated at another time in order to have all data at the same high precision.

The processed data were exported from the GPS and stored in the GIS as vector layers. The GIS layers were then projected using the projection coordinate system of Australia (see

Chapter 4, section 4.4.2). The projected vector layers were overlayed on other terrain attribute layers in order to extract the necessary terrain data.

The field data were collected from the selected road segments (by sampling) and include road layout, road surface, batters, road drainage structures (mitre drains, cross banks, culverts, and roadside ditches), rill and gully features on the road surface and at the outlets of drainage structures, and distance between roads and streams. A road database was also established, using both existing data such as road length and type, from ACT Forests, and data collected in fieldwork. This database includes road surface conditions, road geometry (that is, outsloped, insloped and crowned), cut batter height and slope, vegetation cover on cut and fill batters, slope, road use (for example, occasional and light traffic), year of construction and road width (see Appendix B).

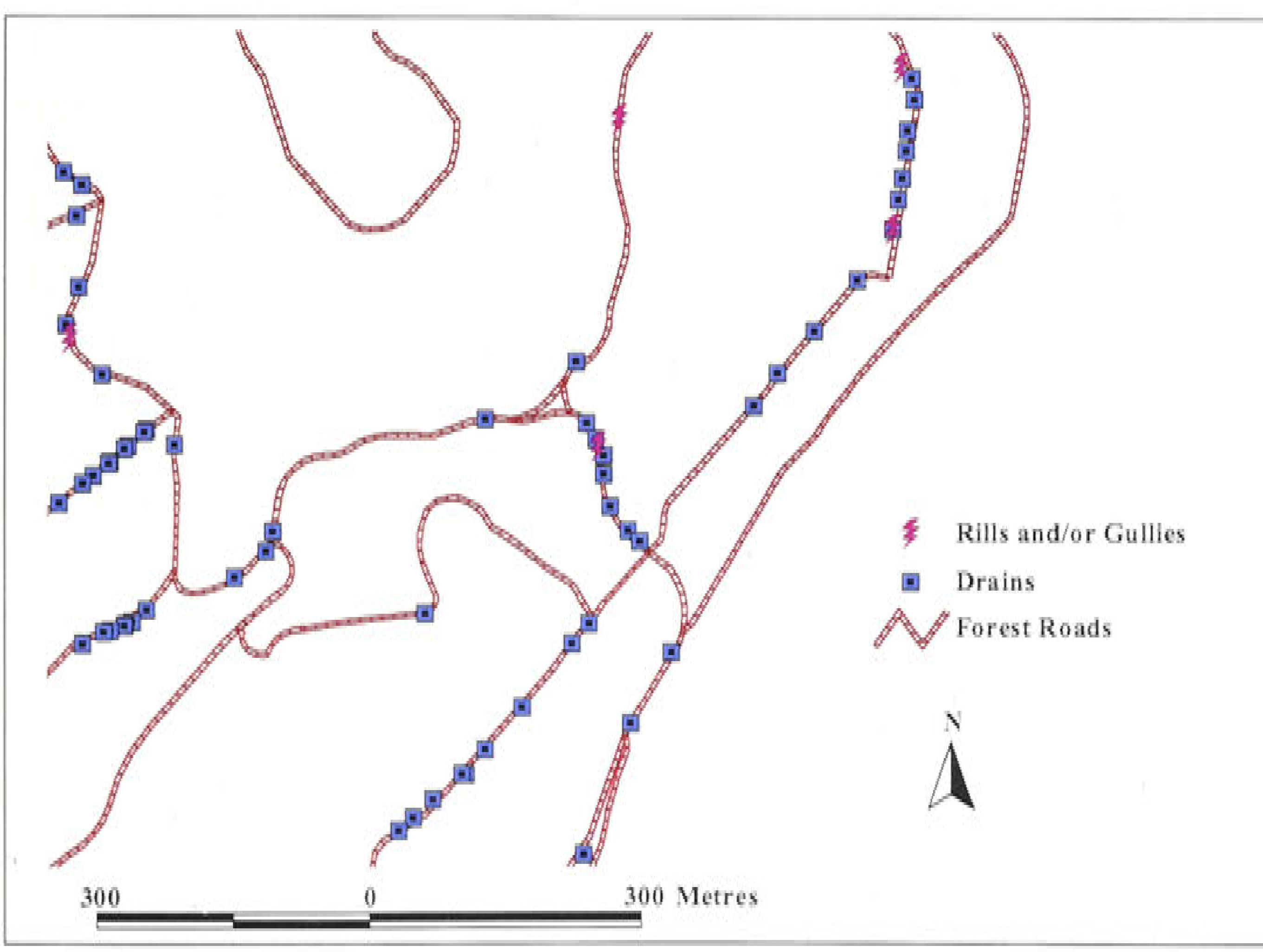


Figure 6.8. Example of the mapped location of the drains and rills and/or gullies on a surface of a forest road

Figure 6.8 shows an example of the mapping of the forest road features using GPS and GIS. The locations of the rills and gullies on the surface of the roads were mapped separately and were overlayed with the road layer to create the final rill and gully location map. Figure 6.9 is a photograph of visible rill and gully erosion on the surface of a road in the Stromlo Forest in 2003. The dimensions of the gully are illustrated in the picture indicating the volume of the soil that was removed from the surface of the road during the gully erosion process (see Appendix E for more photographs).

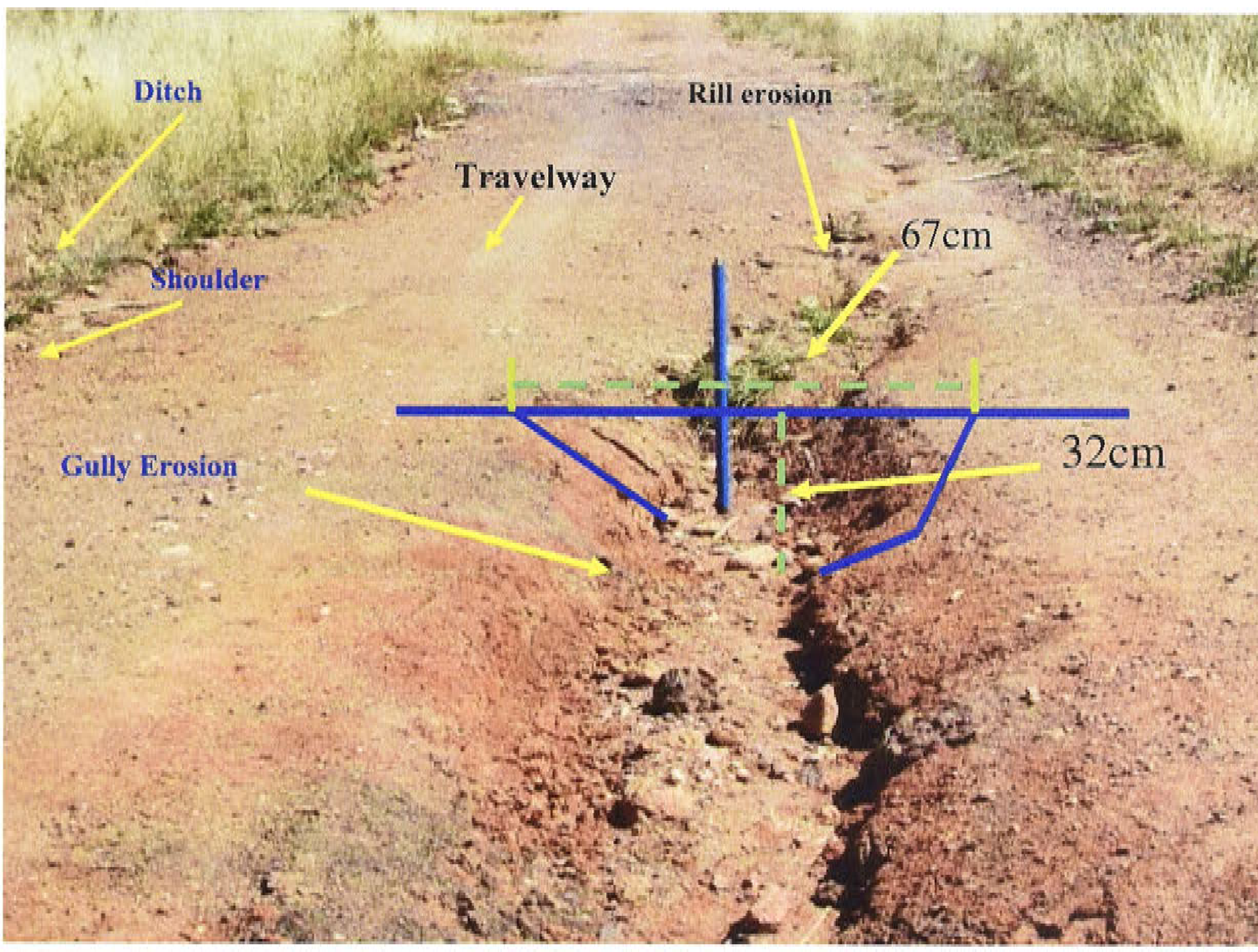


Figure 6.9. An example of rill and gully erosion on the surface of a Stromlo Forest road
Source: Author's photograph, April 2003

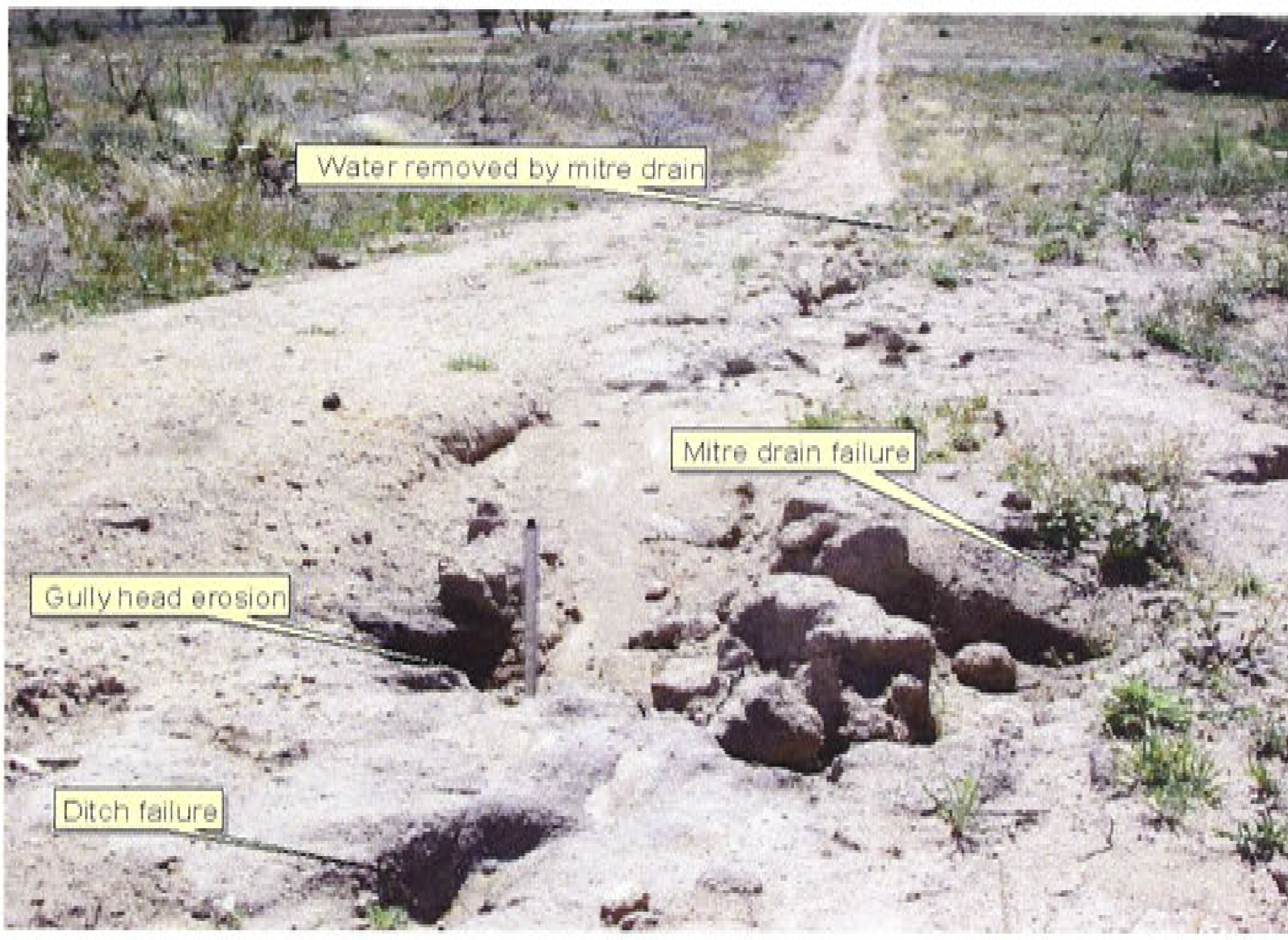


Figure 6.10. An example of table drain (ditch) failure and gully initiation on a Stromlo Forest road
Source: Author's photograph, April 2003

Table 6.16 summarises the variables used in this study, either recorded in the field or derived as terrain attributes by DTM. The hillslope gradient at the outlet of the drains was used for analysing the road to stream connection and for testing the relationship between the variables and rill and gully occurrence at outlets of drains. The hillslope gradient and the road contributing area were used for testing the road-to-stream connectivity (see Chapter 7), using the methodology of Wemple *et al.* (2001), Croke and Mockler (2001) and Hairsine *et al.* (2002). Road contributing width, length and area are the variables necessary for assessing the impact of forest roads in relation to sheet erosion and water quality deterioration. The point and width of the road where the water starts to flow and to drain through a specific road drainage structure, and the endpoint of flow on the road surface, had to be carefully identified. Although this determination calls for some practical field experience, evidence of road slope direction, road geometry, water flow path, and visible evidence of sheet erosion on the road surface were necessary in order to be able to carry out accurate measurement of the road contribution width and length. Accurate field measurement is necessary for accurate estimation of the amount of runoff generation on the surface of the road for each drain, based on contribution area.

Table 6.16. Summary of the variables used in this study

	Identity	Variables	Units	Description
General information	1	ID	Number	Identity of data stored in the database
	2	Field ID	Number	Identity of field recorded data
	3	Drain ID	Number	Drain identity associated with the road segment
	4	Time	-	The time of data recording
	5	Accuracy X	Metre	Horizontal accuracy of recorded data
	6	Accuracy Y	Metre	Vertical accuracy of recorded data
	7	Accuracy Z	Metre	Altitudinal accuracy of recorded data
	8	Direction	Degree	Drain's discharge direction
	9	Drain location	-	Drain's location along the road (left, right)
	10	Position of drain (X, Y)	Degree/metre	Latitude and longitude of drain
	11	Angle of the culvert	Degree	Angle of the pipe or discharge installed on the road
Independent variables	12	Width of road	Metre	Average width of road travelway and shoulder
	13	Road surface slope	Percent	Average slope of road segment
	14	Type of road surface	-	Sealed, unsealed and native surface
	15	Road length	Metre	Length of each road segment
	16	Road geometry	-	Insloped, outsloped and crowned
	17	Road use	-	No traffic, light, occasional, moderate, heavy
	18	Roadside ditch's dimension	Metre	Width, depth and length of ditch (table drain)
	19	Table drains' slope	Percent	Average slope gradient of the channel
	20	Cutslope height	Metre	Average height of the cutslope
	21	Cutslope slope	Percent	Average slope gradient of the cutslope
	22	Cutslope vegetation cover	Percent	Average vegetation cover on the cutslope
	23	Fillslope height and length	Metre	Average height and length of the fillslope
	24	Fillslope slope	Percent	Average slope gradient of the fillslope
	25	Fillslope vegetation cover	Percent	Average vegetation cover on the cutslope
	26	Width of drain's channel	Metre	Average width of mitre drain's channel
	27	Length of drain's channel	Metre	Average length of mitre drain's channel
	28	Depth of drain's channel	Metre	Average depth of mitre drain's channel
	29	Slope of drain's channel	Percent	Average slope of mitre drain's channel
	30	Drain classes	Nominal code	Classification of drain according to construction and working conditions
	31	Road contributing width	Metre	Average width of road segment for a drainage structure
	32	Road contributing length	Metre	Average length of road segment for a drainage structure
	33	Road contributing area	m^2	Area of road segment for a drainage structure
	34	Size of culvert	Metre	Size of the pipe or discharge installed on the road
	35	Culvert classes	Nominal code	Inlet and outlet construction (Concrete, stone, wood, and no construction)
	36	Hillslope	Percent	Slope gradient at the drainage outlets
	37	Water pathway length	Metre	Average runoff length from outlet to streams
	38	Field-measured distance	Metre	Field-measured road-to-stream hydrologic distance
	39	Predicted distance	Metre	Predicted road-to-stream hydrologic distance
	40	Road slope position	-	Valley bottom, midslope, and ridgetop
	41	Elevation	Metre	Elevation of each drain
	42	Aspect	Degree	The slope direction
	43	CTI	Nominal code	Compound Topographic Index
	44	SPI	Nominal code	Stream Power Index
	45	USCA	m^2	Upslope Contributing Area
	46	Plan curvature	$100\ m^{-1}$	Rate of change of aspect along a contour
	47	Profile curvature	$100\ m^{-1}$	Rate of slope change for each cell in slope direction
	48	Tangential curvature	$100\ m^{-1}$	Plan curvature multiplied by sine of the slope angle
	49	Catchment area	Litre or m^3	An area draining to catchment outlet
	50	Flow path length	Metre	Maximum distance of water flow to a point
	51	Slope length	Metre	Total length of slope
	52	Flow direction	Nominal code	Direction of flow from one cell into the target cell
	53	Flow accumulation	Cell number	Upstream catchment area draining into each cell
Dependent variables	54	Rill & gully on road surface	Nominal code	Rill & gully occurrence on the road surface
	55	Rill & gully at drain's outlet	Nominal code	Rill & gully occurrence at the outlet of drains
	56	Road-to-stream connectivity	Nominal code	Connectivity between drain's outlet & streams
	57	Field distance	Metre	Road-to-stream hydrologic distance used for comparison tests with predicted hydrologic distance

Drain location on the left or right sides of the roads, evidence of erosion such as channel formation, sediment plume, and the length of the water pathway were recorded during fieldwork. The distance between road and stream was also measured, using the visible evidence of the water flowpath, from the outlets of the drainage structures down to the stream. This variable was used for comparison of the hydrologic distance between roads and streams predicted by the GIS based model, explained in Chapter 7, for road to stream connectivity.

Data related to each rill and gully – dimension (width, depth, and length), slope, direction, and position – were recorded as individual data sets and then transferred to the GIS from the GPS and stored as a vector layer after projection. The dimensions were used to classify the erosion as rill or gully erosion using the background information provided in Chapter 2. These data were then used to classify the road drainage structures as either 'Yes' (meaning the drain is associated with sheet or gully erosion) or 'No' (meaning the drain is not associated with sheet or gully erosion). These data were also used as dependent variables in correlation and other statistical analyses that are described later.

Most of the roads selected for the field survey had no cut and fill batters of significant height. Therefore, the data and information collected about the cutslopes and fillslopes were limited. However, field observation and data collected from areas with steep terrain around Mount Stromlo show that there were no major cut or slope failures in the study area. This is because the roads were more than 30 years old and the cut and fill batters had become stable over time.

6.3.2 Extraction and Preparation of Terrain Attribute Data

A number of routine procedures such as correction, projection and resampling had to be done before any use could be made of the GIS layers. As the resolution of the original DEM (CRES, 2003) used for the study was 20 metres, those layers which were not built in the same resolution were resampled to 20 metres.

The data were then added into the stored drain vector layer and data sets (see Table 6.16). Elevation, slope, aspect, CTI, SPI, and curvatures are some of the terrain attributes that were extracted from the terrain layers and added into the data sets. The position of the drains (X and Y), and predicted hydrologic distance between road and stream using GIS based models, were also extracted from the layers and added into the data sets.

6.3.3 Variables Used in Developing Predictive Risk Models

The road drainage characteristics, technical information and variables used for analysis in this study were described in Chapter 4, and are listed in Table 6.16. The independent variables used to develop the models predicting the probability of erosion occurrence on the road surface and at the outlet of the drainage structure, and road-to-stream connectivity, are: slope (road surface) gradient, hillslope gradient, cut and fill batters slope gradient and height, road construction year, vegetation cover on cutslope, RCW, RCL, RCA, water pathway length, drain classes, slope position, road use, road geometry, CTI, SPI, USCA, curvatures (profile, plan, tangential, total), aspect, field measured road-to-stream distance, and road-to-stream predicted hydrologic distance.

6.4 Data analysis

Data analysis involved a number of stages. These were: (1) planning; (2) data collection; (3) data management and preparation prior to analysis including, selecting the format of data for a particular software, and defining the dependent and independent variables; (4) selecting the type of statistical analysis (for example, logistic regression) according to the type of dependent variable; (5) presenting the model as an equation and reporting the model development results as tables and graphs; and (6) testing and validating the model using an independent data set. Stages 1 to 4 were described in Chapter 4 and Table 6.16. Details of the model development and validation results are presented in this section. The field data set was partitioned at random into a development and a validation data set, of 254 and 431 data points, respectively. The comparison of the minimum, maximum, mean, standard error, and standard deviation parameters of the variables (for example, RCA, slope, hillslope, CTI, road-to-stream hydrologic distance, and USCA) of both data sets with the population data set, as described in Table 4.5, shows that the development and validation data sets are good samples of the population.

The effect of each independent variable on dependent variables (that is, rill or gully erosion) was tested by applying a sensitivity analysis using stepwise regression, logistic regression, correlation and ANOVA tests, and standard and multiple regression. The individual and combined effects of the variables influencing the probabilities of impacts on soil and water quality were then compared using pairwise and multiple data comparisons. The relationship between a set of independent variables (for example, CTI, SPI, slope and contributing area) and one or more categorical binomial dependent variables was tested using logistic regression. The critical level of significance for all correlation tests is assumed to be $p<0.05$ throughout this thesis.

6.4.1 Model Development

The relationship between all independent variables was tested for rill or gully occurrence on the surface of the road and at the outlets of the drainage structures, in order to identify which variables most influence the probability of the occurrence. The independent variables were identified from most important to least correlated with the elements at risk in the first stage using forward stepwise procedure, simple correlation, and logistic regression analysis (see below and Chapter 7).

Road Surface

Logistic relationships between rills or gullies on the surface of the road, as dependent variable, and the independent variables described in Table 6.16 were fitted using a forward stepwise procedure. Independent variables entered the model in the order of decreasing linear correlation (Chapter 4, section 4.7.2) until there were no significant improvements to the equation statistics.

The best logistic model to classify rill or gully occurrence on the surface of the road (equation 6.1) included RCA, slope and CTI as significant parameters ($p<0.0001$) and correctly classified over 96% of the observed presence and absence of rills or gullies (Table 6.17). There is no evidence of a lack of fit (Hosmer and Lemeshow $\chi^2 = 4.04$, $p>0.85$). Further details of the model fitting and testing are presented in Appendix D. The overall logistic model for rill and gully occurrence on the road surface, based on equation 4.11 described in section 4.7.2 (Chapter 4), and estimated parameters, presented in Appendix D, Table 3, is:

$$\underset{[3.309]}{Y_i = -16.77} + \underset{[0.121]}{0.121} * RCA_i + \underset{[0.120]}{0.395} * Slope_i + \underset{[0.346]}{0.934} * CTI_i \qquad (6.1)$$

where [] denotes standard error;
Y_i denotes odds of a rill or gully on the road surface i;
RCA_i denotes Road Contributing Area i;
$Slope_i$ denotes road surface slope gradient i in percent;
CTI_i denotes Compound Topographic Index i.

Table 6.17. Classification table for results of road surface rill and gully erosion prediction

Rill or Gully Observation	Rill or Gully Erosion Prediction		
	False ($P_i < 0.50$)*	True ($P_i \geq 0.50$)	Correct prediction (%)
Not observed	104	5	95.4
Observed	5	104	96.6

* $P_i = 1/[1 + \exp(-Y_i)]$

Outlets of Road Drainage Structures

The same analytical approach described above for the road surface was applied in evaluating the logistic relationships between the independent variables and the rill or gully occurrence at the outlets of the road drainage structures. The best logistic model to classify rills or gullies at the outlets of the road drainage structures (equation 6.2) included RCA, hillslope gradient and USCA as significant parameters ($p<0.0001$), and also correctly classified over 96% of the observed presence and absence of rills or gullies (Table 6.18). There is no evidence of a lack of fit (Hosmer and Lemeshow $\chi^2 = 3.66$, $p>0.88$). Further details of the model fitting and testing are presented in Appendix D. The overall logistic model for rill and gully occurrence at the road drainage structures, based on equation 4.11, and estimated parameters presented in Appendix D, Table 10, is:

$$\underset{}{Y_i = \underset{[1.72]}{-8.980} + \underset{[0.018]}{0.055} * RCA_i + \underset{[0.093]}{0.227} * HSG_i + \underset{[0.005]}{0.012} * USCA_i} \tag{6.2}$$

where [] denotes standard error;
Y_i denotes odds of a rill or gully at the outlets of road drainage structures i;
RCA_i denotes Road Contributing Area i;
HSG_i denotes hillslope gradient i in percent;
$USCA_i$ denotes Upslope Contributing Area i.

Table 6.18. Classification table of results of road drainage structures rill or gully erosion prediction

Rill or Gully Observation	Rill or Gully Erosion Prediction		
	False ($P_i < 0.50$)*	True ($P_i \geq 0.50$)	Correct prediction (%)
Not observed	103	6	94.5
Observed	4	142	97.0

* $P_i = 1/[1 + \exp(-Y_i)]$

The statistical analysis showed that some variables were not significant when tested as components of the model in the study area. For example, road slope position (valley bottom, midslope and ridgetop), road geometry (insloped, outsloped and crowned), road use and traffic, cutslope height and vegetation coverage were not significant factors in predicting rill and gully erosion on the surface of the roads. The cutslope contribution to erosion is relatively small compared to that of other road elements when the cutslope height is less than 3 m (Tysdal *et al.*, 1999). The height of cutslopes recorded from the field survey is mostly less than 1 m and, as explained in section 6.2.1, both cutslopes and fillslopes have become stable over time. Road construction year (decade) was also not a significant factor in occurrence of the surface erosion, as almost 99% of the roads were built more than 30 years ago. According to Megahan *et al.* (1986) and Burroughs and King (1989), most road sediment is produced within the first two years after road construction, but continues at a reduced rate for quite long periods.

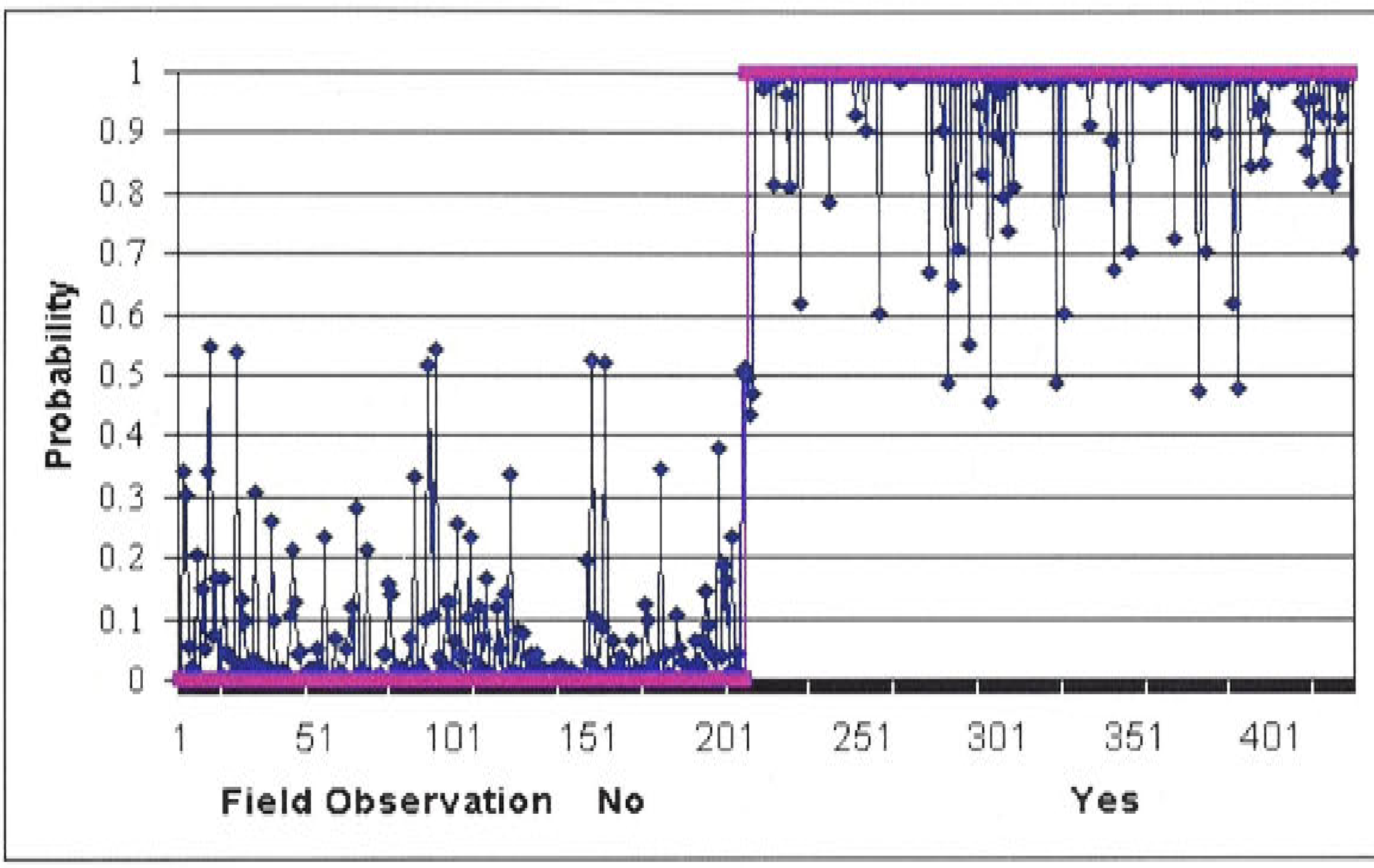
6.4.2 Model Validation

The primary objective of the model development was to provide a model capable of assessing the impact on water quality of erosion associated with unsealed forest roads. The aim of the validation of the logistic models predicting rill and gully erosion on the road surface and at the outlet of drainage structures is to test the models' predictive accuracy.

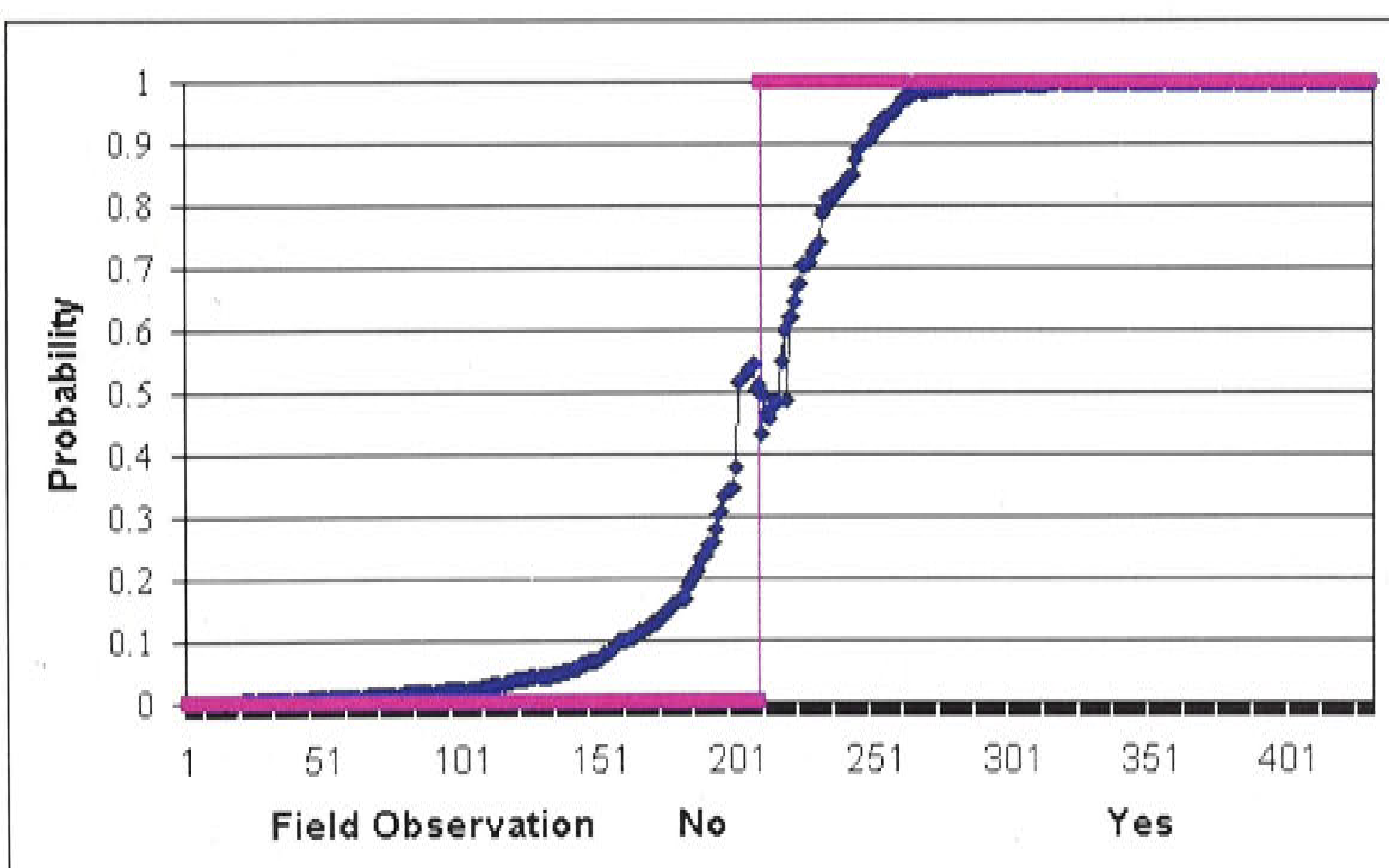
The judgment of validity of a model depends on the circumstances in which the model is applied and the predictive accuracy of the model. There are two types of validated model: (1) a statistically validated model is one which passes all appropriate statistical checks, including goodness-of-fit, residual and ROC analyses on the development data set (see Appendix D) and; (2) a practical validated model is one which performs satisfactorily on a validation data set to provide unbiased prediction on a new data set. As mentioned above, the models passed all of the statistical validation processes applied during the model development stages. As described in Chapter 4, the selection of an appropriate sample of data (that is, a validation data set) is of great importance in performing a practical model validation. Gilbert (1993) points out that a model that has been developed to explain data taken from one context (development) is very frequently tested on data derived from different but related contexts (validation).

Road Surface

An independent validation data set, as described in section 6.4, was used to validate the logistic model developed for predicting the probability of rill or gully erosion occurrence on the road surface. The presence or absence of rills and gullies on the road surface for these data was estimated using the fitted logistic function (equation 6.1) and found to match the observed condition on 96% of occasions (Figure 6.11b). The 4% of cases where equation 6.1 did not result in a correct classification of gullies and rills were limited to those conditions where the probability predicted by the equation was between 0.43 and 0.55; that is, there was total agreement between the model and the observations when the model is predicted outcomes were less than 0.43 or greater than 0.55. This is a relatively small range where the model predictions are uncertain and indicates that equation 6.1 is generally a valid and useful model.



A

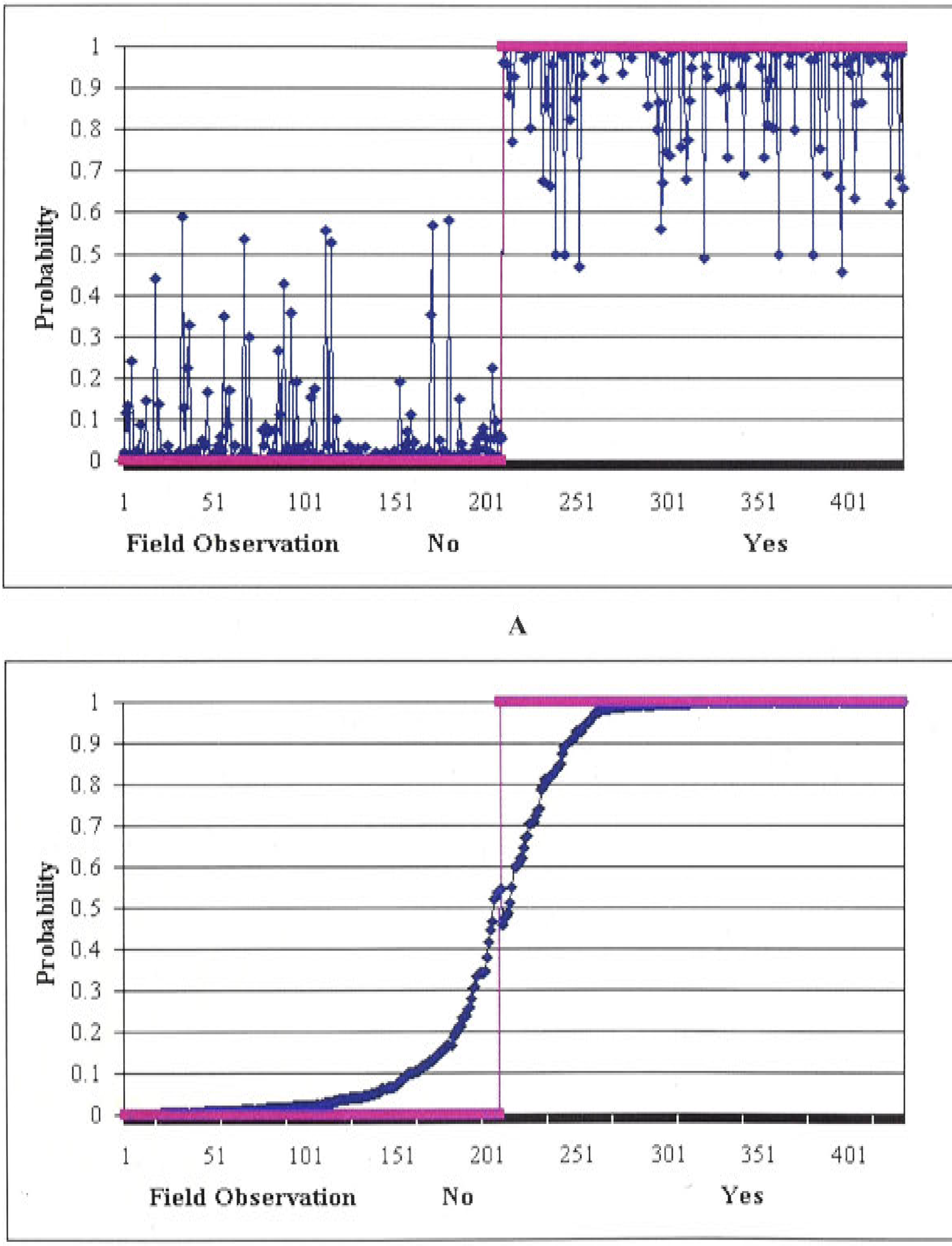


B

Figure 6.11. Probability of rill and gully occurrence on the road surface predicted by the model versus field observation. A: Scattered distribution. B: Nonlinear distribution showing discontinuity when predictions were incorrect

Outlet of Drainage Structures

The same processes as described above for erosion from the road surface were applied to validate the logistic developed model for erosion from the outlets of the road drainage structures (equation 6.2). The presence or absence of rills and gullies at the outlets of road drainage structures for validation data was estimated using the fitted logistic function (equation 6.2) and found to match the observed condition on 96% of occasions (Figure 6.12b). The 4% of cases where equation 6.2 did not result in a correct classification of gullies and rills was limited to those conditions where the probability predicted by the equation was between 0.45 and 0.58; that is, there was total agreement between the model and the observations when the model predicted outcomes were less than 0.45 or greater than 0.58. As for the model for the road surface erosion, this is a relatively small range, and indicates that equation 6.2 is generally a valid and useful model.



A

B

Figure 6.12. Probability of rill and gully occurrence at the outlets of road drainage structures predicted by the model versus field observation. A: Scattered distribution. B: Nonlinear distribution showing discontinuity when predictions were incorrect

6.5 Mapping the Risk of Rill and Gully Occurrence on the Road Surface and at the Outlets of Drainage Structures

A combination of the independent variables assessed as risk factors influencing rill and gully erosion on the road surface and at the road drainage structures (equations 6.1 and 6.2), and those describing the risk ranking, was used to produce a risk map. These variables are RCA, slope gradient and CTI for road surface, and RCA, hillslope gradient and USCA for outlets of road drainage structures. To create road surface and road drainage outlet risk components, scores were assigned for each of the variables using the criteria defined and described in Chapter 4, section 4.8. The independent variables listed above were aggregated using ArcGIS by adding the single score for each area in each pixel to produce an aggregated score for road surface and road drainage outlet risk components.

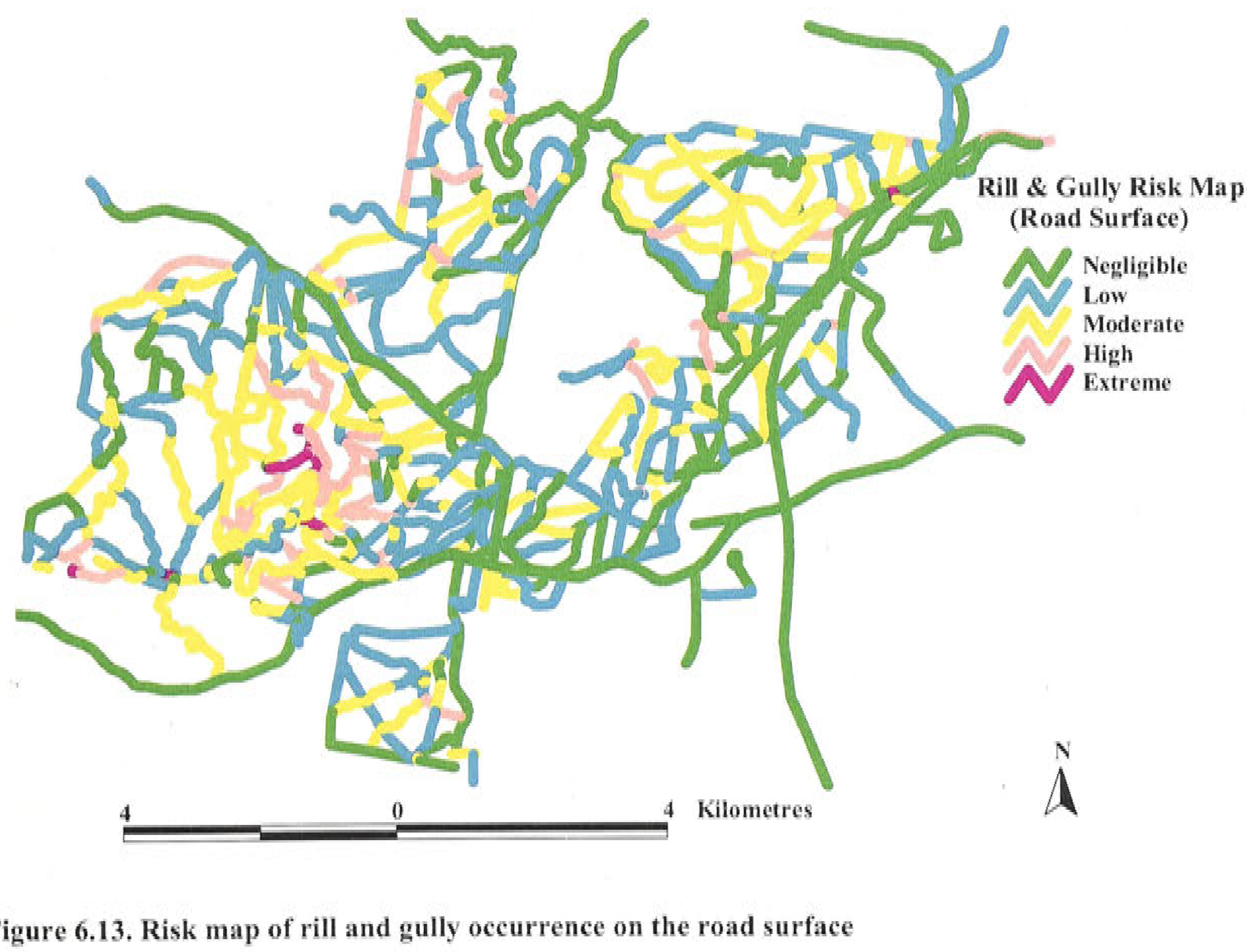


Figure 6.13. Risk map of rill and gully occurrence on the road surface

Figure 6.13 presents the mapped risk of rill and gully occurrence on the road surface. The risk was first ranked for the sampled road segments according to the variables assessed as significant risk factors influencing rill and gully occurrence on the road surface in the model development, testing and validation processes, and then was generalised to create a risk map for all of the road segments of the study area. According to British Columbia Environment (1995a), Ryan *et al.* (1998), Australian Government (2000), Macdonald *et al.* (2001) and Croke and Mockler (2001), the likelihood of sheet erosion on the road surface is very low when the slope gradient of the road surface is low and the road is located in a flat area. Roads are not at risk in terms of rill and gully erosion or landslide occurrence when the slope gradient is less than 5% (British Columbia Environment, 1995a; Ryan *et al.*, 1998). For example, the likelihood of rill and gully erosion occurrence under these circumstances would be 'rare' (level 1), and 'unlikely' (level 2). In this situation, the consequences of rill and gully erosion, if it should happen, would be 'insignificant' (level 1) or 'minor' (level 2). The risk ranking scores associated with these levels of likelihood and consequences would be 1 - 4, and the risk level associated with these scores 'negligible' and 'low', respectively.

Road contributing area (RCA) is another variable assessed as a significant risk factor influencing the rill and gully erosion, both on the road surface and at the outlet of drainage structures. The greater the RCA, the greater the volume of runoff on the road surface, which may cause high erosion rates, increase the possibility of rill and gully occurrence on the road surface, and increase sediment movement from the road surface and outlet of drainage structure down into an adjacent stream. Croke and Mockler (2001) stated that there is a high possibility of gully erosion at drainage outlets when the RCL and RCA values are more than 25 m and 70 m^2, respectively. The likelihood of rill and gully occurrence on the road surface or at the outlet of drainage structures would be 'negligible' (level 1) and 'low' (level 2) when the RCA is small (for example, less than 40 m^2). In this situation, the consequences of rill and gully erosion, if it should happen, would be 'insignificant' (level 1) or 'minor' (level 2); the risk scores associated with these levels of likelihood and consequences would be 1 - 4, and the risk levels associated with these scores are 'negligible' and 'low', respectively. When the RCA exceeds 70 m^2, the likelihood of rill and gully occurrence on the road surface and at the outlet of drainage structure would range from 'possible' (level 3) to 'almost certain' (level 5) and the consequences would be 'moderate' (level 3) to 'catastrophic' (level 5). The risk scores associated with these levels of likelihood and consequences would be between 9 and 25, and the risk level associated with these scores is between 'moderate' and 'extreme'.

CTI is the third variable assessed as a significant risk factor influencing the rill and gully erosion on a road surface. As described in Moore *et al.* (1993), the CTI value is used to predict the spatial distribution of saturation zone and the propensity of the overland flow. The smaller the CTI value, the lower volume of the overland flow, which may decrease the likelihood of sheet erosion occurring. The likelihood of rill and gully occurrence would be between 'possible' (level 3) and 'likely' (level 4) when the CTI value exceeds 8; in this situation the consequences would be between 'minor' (level 2) and 'major' (level 4). The risk scores associated with theses levels are between 6 and 16, and the risk levels associated with these scores are between 'moderate' and 'extreme'.

Table 6.19. Summary of risk evaluation results for rill and gully occurrence on the road surface

Risk classes	All roads		Surveyed roads	
	km	%	km	%
Negligible	96	31	37	36
Low	98	32	33	32
Moderate	88	29	25	25
High	22	7	6	6
Extreme	3	1	1	1
Total	307	100	102	100

Table 6.19 summarises the results of the risk evaluation by each risk class; in this and subsequent tables, the 'road network' is referred to as 'all roads'. As shown in the table, 63% of the road network and 68% of the surveyed roads are classified as having 'negligible' and 'low' risk, while only 8% of all roads and 7% of the surveyed roads are associated with 'high' and 'extreme' risk classes. Less than 29% of all roads and 22% of the surveyed roads are classified as having 'moderate' risk level.

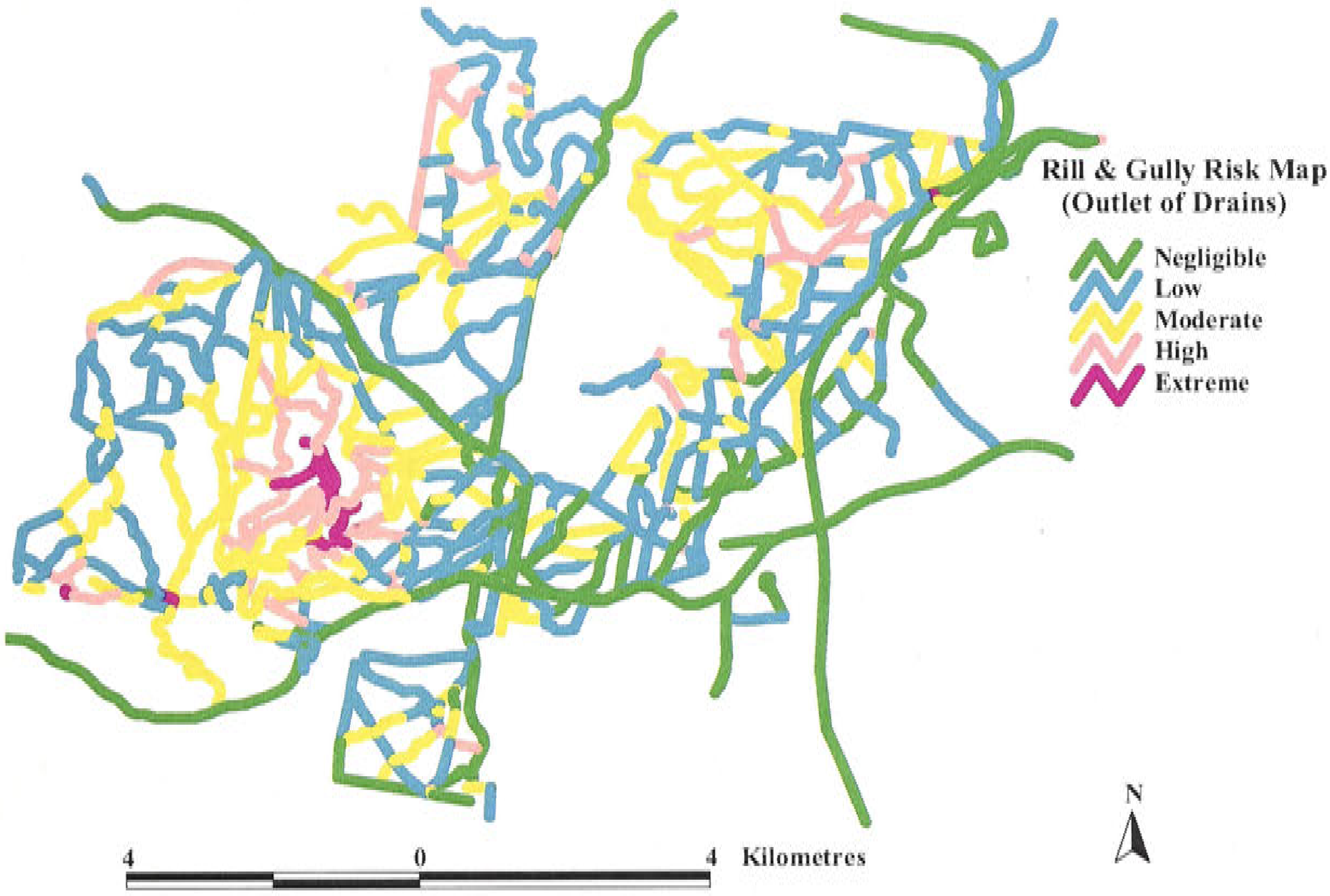


Figure 6.14. Risk map of rill and gully occurrence at the outlet of drainage structures

Table 6.20. Summary of risk evaluation for rill and gully occurrence at the outlet of drainage structures

Risk classes	All roads		Surveyed roads	
	km	%	km	%
Negligible	61	20	23	23
Low	111	36	39	38
Moderate	92	30	27	26
High	36	12	11	11
Extreme	7	2	2	2
Total	307	100	102	100

Figure 6.14 shows the road segments at different levels of risk according to the risk assessment of rill and gully erosion at the outlets of the road drainage structures. The same processes described above were used to determine the level of risk associated with the road segments. As can be seen from Table 6.20, more than half of all roads and 61% of the surveyed road segments are assessed as having 'negligible' or 'low' risk levels. About 14% of all roads and 13% of the surveyed roads are classified in 'high' or 'extreme' risk level,

while 'moderate' risk is associated with about 30% of all roads and 26% of the surveyed roads.

A comparison of the results summarised in Tables 6.19 and 6.20 shows that around 40% of the surface of the roads is classified as 'moderate' or higher risk levels, while nearly half of the roads are at these risk levels for erosion associated with the outlets of road drainage structures. This also indicates that the high and extreme risks associated with the outlets of road drainage structures are twice as great as those associated with the road surface. One of the most important reasons for this is related to the magnitude of the slope gradient: the slope gradient value of the road surface is usually smaller than the hillslope gradient. The average slope gradient of road surface is about 11%, and that for hillslope gradient is about 17%. Therefore, the effect of this factor in terms of influencing rill and gully occurrence on road surface is smaller than at the outlets of road drainage structures.

6.6 Summary and Conclusions

A DEM with 20 m resolution was used to create terrain attribute layers using DTM. Field data, DEM and terrain attribute layers provided the data sources used in this study. Preparation routines such as georegistration, projection, resampling (where needed), correction, and calculation of the attributes were applied to the terrain GIS layers in order to prepare them for analysis. Although preparation of the GIS layers (terrain attributes and field data) was time consuming, it was necessary in order to create component layers and/or tabulate data and to test the effects of the independent variables on the dependent variable.

The slope stability index was calculated and mapped for the catchment area and for the forest road network using the SINMAP extension of ArcView GIS. The results show that most forest roads are located in stable and moderately stable areas, at 79 and 10%, respectively. More than 5% of the roads are located in areas of probable instability. However, field assessment and observations did not support the predicted SI for the forest roads, as the roads were built more than 30 years ago and have become stable over that time.

A 'development' data set from the field surveys was used to develop the risk prediction models used to estimate the probability of rill and gully occurrence on the surface of the roads and at the road drainage structures. The data set comprised 254 data points from the road surface characteristics, the characteristics of the road drainage structures, terrain attribute data from the DTM, and the locations and characteristics of rill or gully erosion on the road surface and at the outlets of the road drainage structures. In addition, all road segments selected for field survey were assessed for any evidence of cut or fill batter failures. Data collected in the field and derived from the DEM (terrain attributes) were analysed in order to develop a predictive model and find the most important independent variables influencing the impacts of forest roads on the soil and water.

Evaluating the relationship between the dependent variable and the best subset of the independent variables, using logistic regression, ROC and goodness-of-fit, demonstrated that a significant relationship exists between some of the independent variables and rill and gully occurrence on the road surface and at the outlets of the road drainage structures. The results of the analyses presented in this chapter demonstrate the importance of contributing road length and area, slope, upslope contributing area, and CTI in predicting rill and gully erosion on the road surface. The residual, goodness-of-fit and ROC tests have also shown that the final models provide a good fit to the data.

A 'validation' data set, comprising the other 431 data points partitioned randomly from the overall data set, was used to validate the model developed from the 'development' data set. The results of model validation show that both road surface and drainage outlet models can correctly predict the probability of rill and gully occurrence on the road surface and at the road drainage structures more than 96% of the time. This confirmed the hypothesis of the study introduced in Chapter 1, that the use of the terrain attribute data can predict rill and gully erosion from the road system.

Chapter 7
Results and Discussion 3: Predicting the Probability and Risk of Road-to-Stream Connectivity

7.1 Introduction

The delivery of sediment to streams depends principally on the degree of hydrologic connectivity between roads and streams (Takken *et al.*, 2005). The importance of this parameter and associated issues were discussed in Chapter 4, section 4.6. As outlined in Table 4.1 (Chapter 4), the process of predicting the probability and risk of the road-to-stream connectivity involved four principal steps: (1) road analysis; (2) hydrologic analysis; (3) development of rill and gully occurrence and road-to-stream connectivity risk models, and; (4) risk assessment and mapping. Implementation of each of these in this chapter is summarised below.

1. Forest road analysis

1.1 Digitise the road network from spatial information
- Verify road network and map drainage location

1.2 Assess erosion risk associated with road and drainage structures
- Classification of road drainage structures and road layers

1.3 Conduct road slope position analysis

1.4 Extract relevant terrain attribute values

1.5 Assemble spatial data sets and create single integrated data set

Steps 1.1, 1.4 and 1.5 of the road analysis were discussed in Chapters 4 and 6. Steps 1.2 and 1.3 will be discussed in this Chapter, which explains how the analysis was conducted, including how well the road drainage structure works in terms of discharging the water from the road segments, the drainage and road classification used, and the slope position of the roads.

2. Hydrological analysis

2.1 Conduct stream and watershed delineations;
2.2 Mode the road-to-stream hydrologic distance using five GIS-based models;
2.3 Assess road-to-stream hydrologic connectivity using statistical and GIS-based approaches

3. Development of rill & gully occurrence and road-to-stream connectivity risk models

3.1 Data preparation
3.2 Develop models
3.3 Test and validate the models

This Chapter (section 7.3) describes the hydrologic analysis which comprises watershed delineation, road-to-stream hydrologic distance prediction, and road-to-stream connectivity prediction. Watershed delineation was carried out using the basin and the hydrologic modelling extensions in ArcView and ArcInfo commands, to create basins, sub-watersheds and stream layers. These layers were then used for road-to-stream hydrologic distance prediction and road-to-stream connectivity assessments.

The road-to-stream hydrologic distance was predicted using five GIS-based models: the ArcInfo *NEAR* method, and the *FLOWLINES, SFLINES, FLOWPATH* and *DISTWASH* models (ESRI, 1994; Newham and Croke, 2002; Takken, 2003). MapWin and the TauDEM (Tarboton, 2004) extension for ArcGIS were used for predicting the road-to-stream hydrologic distance. The DEM, stream and road drainage layers were used as input layers to the models. All models use the location of the road drainage structures to predict the future location of a flow in order to compute the water flow length (hydrologic distance) of each drain to the nearest streamline. The aim of applying these different models was to compare several alternative methods of estimating the distance between the outlets of the drain and the stream. The results of modelling the different methods were each compared with the distance measured in the field in order to find the best prediction for hydrologic distance.

The type of the road-to-stream connectivity – stream crossing (direct connectivity), diffuse (overland flow), and gully connectivity – was assessed by a number of methods: (1) field observation, for verification and validation of the connectivity predicted by models; (2) use of threshold curves developed by Croke and Mockler (2001) for predicting gully and non-gully connectivity; (3) use of Vbt5 model developed by Hairsine *et al.* (2002) for predicting diffuse connectivity, and; (4) intersecting the road and the stream layers to locate stream crossings and direct connectivity.

A logistic model for predicting the road-to-stream hydrologic connectivity was also developed following the process described in Chapter 6 for predicting rill and gully erosion on the road surface and at the outlets of the road drainage structures. The model was developed using the 'development' data set, and tested and validated using the 'validation' data set.

4. Risk assessment and mapping

4.1 Identify risk
4.2 Analyse the risk
4.3 Create risk maps

The final step in the process was the mapping of road-to-stream connectivity using information and results from the previous three steps. The final road-to-stream risk map (Figure 7.19) shows the degree of the connectivity between roads and streams; this can be used to identify which road segments are more likely to connect to the stream and thus have the greatest potential water quality impacts.

7.2 Road Analysis

7.2.1 Classification of Drainage Structures

Road Drainage Structures Characteristics

In Stromlo Forest, as described in Chapter 4, section 4.3.3, the roads are drained by a variety of drainage structures, including roadside table drains, mitre drains, cross-banks, push outs and culverts (relief and stream crossing). Mitre drains are the major drainage structures (Table 7.1). In the study area, relief culverts were installed at some locations on the forest roads, mostly on the slopes of Mount Stromlo and adjacent roads. These roads are located in the midslope and ridegetop slope positions (Figure 7.1). The field survey of the roads showed most of the erosion was originally initiated where it was impossible to install proper ditches or to discharge the runoff from the ditches. This was because of the topographic position of the road segment and its hillslope gradient. In these cases, the runoff flowed through the ditches for some distance and was redirected back onto the surface of the roads. The runoff problem was exacerbated during and after heavy storm events.

Table 7.1. Drain characteristics surveyed and sampled

Drainage structures surveyed		Development data set		Validation data set		Field survey (Population)	
		N	%	N	%	N	%
Culverts		33	13	48	11	81	11.8
Mitre drains		199	78	361	84	560	81.8
Push outs		4	2	7	2	11	1.6
Cross banks		18	7	15	3	33	4.8
Total		254	100	431	100	685	100
Average value of RCL (m)	Drains	40		42		41	
	Culverts	85		79		82	
	Average for all drainage structures	46		46		46	
Average value of RCA (m^2)	Drains	57		60		59	
	Culverts	126		117		121	
	Average for all drainage structures	66		66		66	
Slope at outlet (%)	Highest	56		52		57	
	Lowest	3		1		3	
	Average for all drainage structures	17.2		16.4		16.7	

Table 7.1 summarises the characteristics and types of road drainage structures included in the field survey data set, the development and validation data sets. The characteristics of the data sets are presented in Chapter 4, section 4.3.4, and Chapter 6, section 6.4. A total of 685 drainage structures from the 102 km of selected forest roads in the study area were surveyed as the field survey (population) data set. This set includes 604 drains and 81

culverts (two of which were bridges over streams). The majority of the drainage structures surveyed were mitre drains (about 82%); however, culverts dominated on steep terrain, especially around Mount Stromlo itself (Table 7.1). About 5% (33 out of 685) of the drainage structures surveyed were cross-banks installed on snig tracks on steep terrain. Only a small number of surveyed drains (1.6%) were push-out drainage structures. About 13% and 11% of selected sample drainage structures for development and validation data sets, respectively, were culverts. The majority of drainage structures selected for developing the models were mitre drains (78%), while 2% and 7% of them were push-outs and cross banks, respectively (Table 7.1).

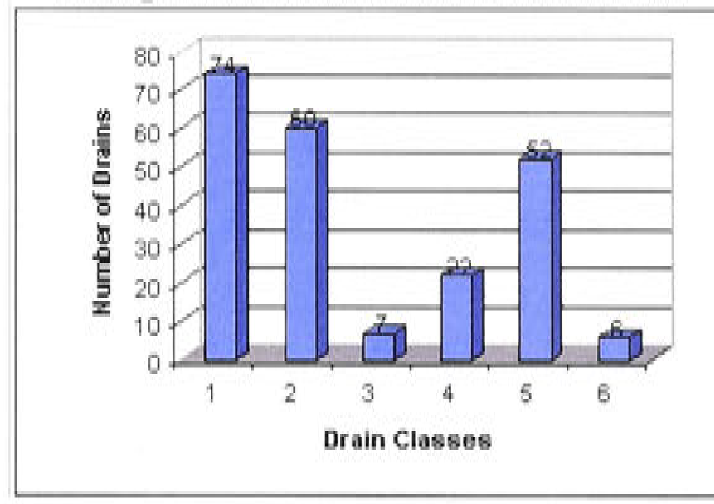
Table 7.1 shows that the average values of the road contributing length (RCL) for drains (mitre drains, cross banks and push outs) were 40, 42 and 41 m for development, validation and field survey (population) data sets, respectively. The RCL values for culverts were around twice that, at 85, 79 and 82 m, respectively. The average value of RCL for drainage structures for all data sets was 46 m. The average values of road contributing area (RCA) for drains and culverts from population were 59 and 121 m^2, respectively, for development data set, they were 57 and 126 m^2, and for validation data set, they were 60 and 117 m^2, respectively. The average RCA of all drainage structures was 66 m^2 for both field survey and development data sets. The highest value of slope gradient at the outlet of drainage structures was 57% for field survey and 56% and 52% for development and validation data sets, respectively. The lowest and average values for both field survey and development data sets were 3 and about 17%, respectively, while they were 1% and 16.4% for the validation data set, respectively.

Classification of the Road Drainage Structures

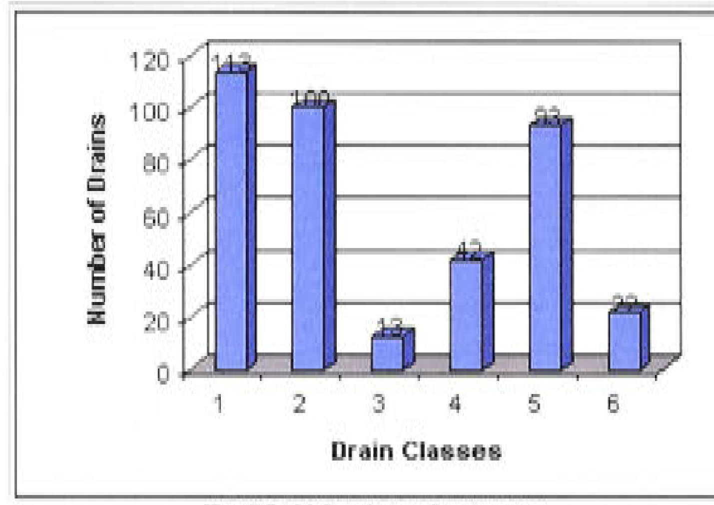
The classification of drains into six groups was described in Chapter 4, section 4.3.3. Figure 7.1 summarises the results of the classification of drainage structures of the population and development data sets in the study area. Drain class (condition) was not recognised as a significant independent variable influencing rills and gullies on the road surface; however, the field assessment shows that a few failed drains were associated with rill or gully erosion on the surface of the roads.

D.C.*	Des.*	Development data set		Validation data set		Field survey data set	
		N	%	N	%	N	%
1	B.C.*, working	74	33	113	30	187	31
2	B.C., partly working	60	27	100	26	160	27
3	B.C., not working (blocked)	7	3	13	3	20	3
4	N.B.C.*, but working	22	10	42	11	64	11
5	N.B.C., partly working	52	24	93	24	145	24
6	N.B.C., blocked	6	3	22	6	28	5
Total	-	221	100	383	100	604	100

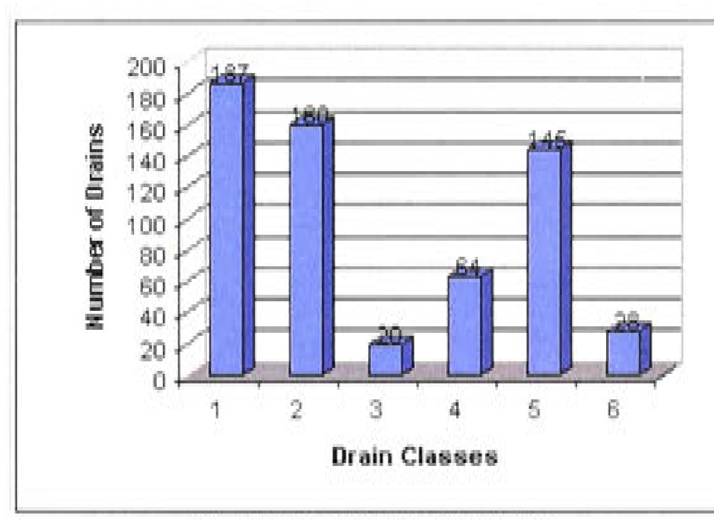
Histogram of the drain class distribution



A: Development data set



B: Validation data set



C: Field survey data set

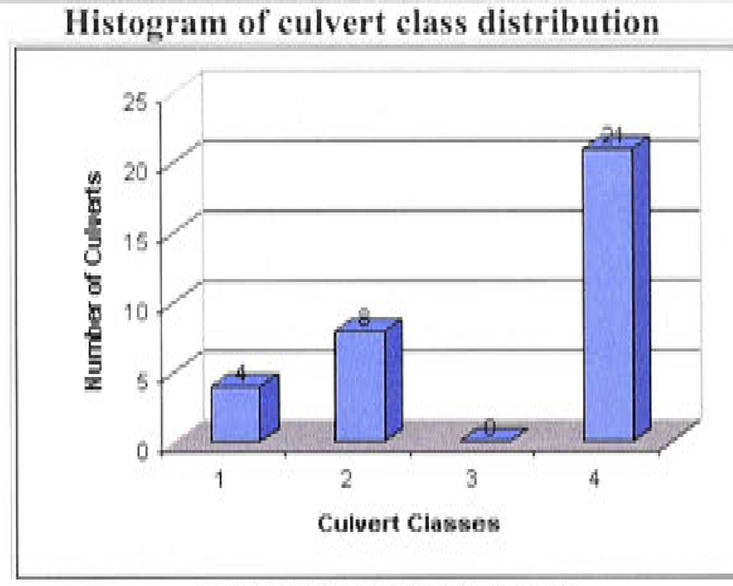
Figure 7.1. Classification of surveyed drains in development, validation and field survey data sets

* D.C. = Drain class, Dis. = Description, B.C. = Built correctly, N.B.C.= Not built correctly

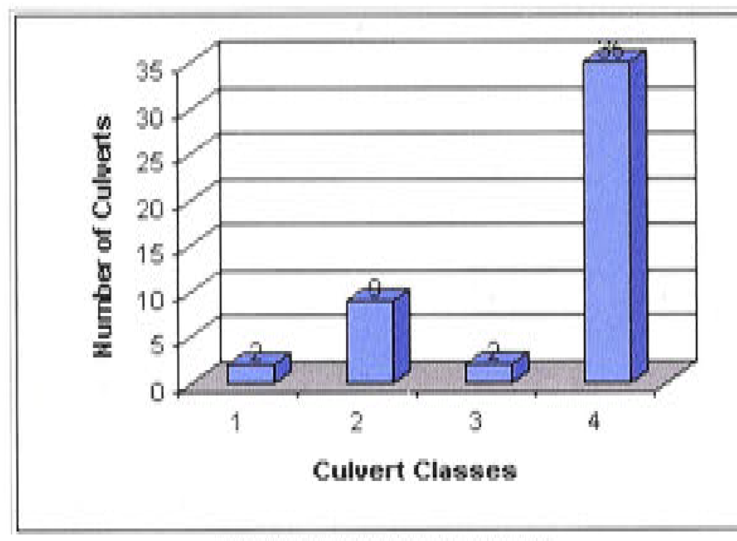
As shown in Figure 7.1, in all data sets (development, validation and field survey), most drains were classified as classes 1, 2 and 5. About one third of the drains in all data sets were classified as class 1 (built correctly, working well). Less than 6% of drains in all data sets were completely blocked (classes 3 and 6). Class 4 (drains not built correctly but working well in terms of discharging runoff) characterised 10, 11 and 11% of the development, validation and field survey data sets, respectively.

C.C.*	Des.*	Development data set		Validation data set		Field survey data set	
		N	%	N	%	N	%
1	Built of concrete	4	12	2	4	6	7
2	Built of Stone	8	24	9	19	17	21
3	Built of Wood	0	0	2	4	2	3
4	No Con.*	21	64	35	73	56	69
Total	-	33	100	48	100	81	100

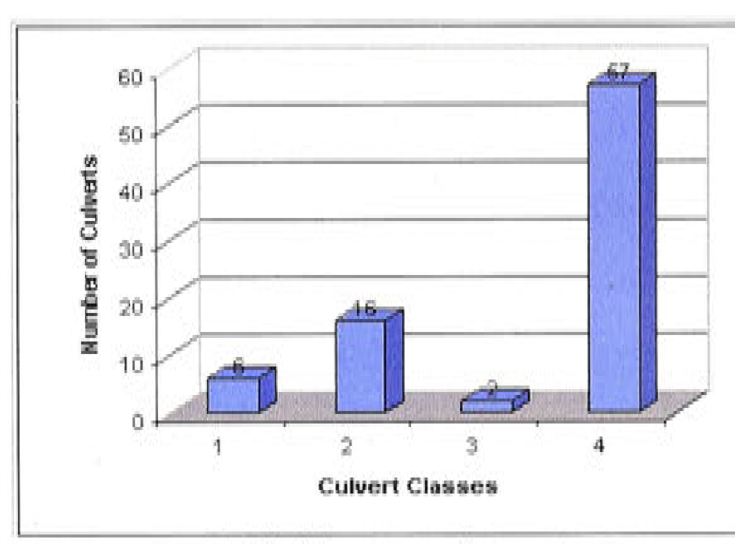
Histogram of culvert class distribution



A: Development data set



B: Validation data set



C: Field survey data set

Figure 7.2. Classification of culverts in development, validation and field survey data sets

* C.C. = Culvert class, Dis. = Description, No Con. = No construction

As described in Chapter 4, section 4.3.3, culverts were classified into four groups based on the type of construction at the inlet and outlet. A common problem influencing culvert drainage failure is a lack of construction at the inlet or outlet of the culvert. Figure 7.2 summarises the results of the culvert classification survey. The majority of culverts surveyed, 64% of development data set, 73% of the validation data set, and 69% of field survey data set have no construction (class 4) at the inlet and outlet.

Only 7% (6 of 81) of the outlets and inlets of the culverts from the field survey data set, 12% (4 out of 33) from development data set and 4% (2 of 48) of validation data set were made of concrete (class 1). About 21% (17 of 81) of the culverts from field survey data set, 24% (8 of 33) from development data set and 19% (9 of 48) from validation data set were classified as class 2. Only 3% of the outlets and inlets of culverts from field survey and 4% from validation data sets were built of wood (class 3); none of these were selected for inclusion in the development data set.

7.2.2 Classification of the Forest Road Layer

Road Class

Each road in the forest road network of the study area was classified based on the accessibility of the road, the width of the road, and whether or not the road surface was sealed. This classification was derived from those used by State Forests of NSW (1999) and Forestry Tasmania (2000), and information from the Stromlo Forest GIS layer (ACT Forests). The classification is summarised in Table 7.2. The width of the Stromlo Forest roads is commonly less than 6 m, except for public roads. Most of the tracks were less than 4 m in width and are classified as class 5. The field survey showed the width of the minor access roads is mostly between 3.5 and 5 m, except in switchback areas (Table 7.3).

Table 7.2. Classification of forest roads of study area

Road class	Formation or pavement width (m)*	Function*	Road surface pavement type and conditions*
1	>5.5	Primary road in large network, public roads	Surfaced, all-weather
2	5.5	Secondary access road, major access	Surfaced, two lanes, all-weather
3	3.7 – 4.0	Feeder and spur, minor access	All-weather road, unsealed, two lanes
4	3.7	Feeder and spur road, minor access	Dry weather track, unsealed, loose surface
5	3 – 3.7	Harvesting roads, tracks	Dry weather track, unsealed, loose surface
6	3 – 3.7	Fire trail, Walking tracks	Four wheel drive track

* Forestry Tasmania (2000) and State Forests of NSW (1999). Forestry Tasmania (2000) uses the terminology 'road surface pavement type and width' and State Forests of NSW (1999) uses 'formation width and road surface condition'.

Most of the forest roads in the study area were classified as being in classes 3 to 5 (except for public roads), because of their width and surfacing. The field observations concur with the ACT Forest road database, in that all 'minor access' and most 'major access' roads are unsealed, but are accessible in all seasons and almost all weather conditions. Table 7.3 summarises the type, class and length of forest roads and surveyed forest roads of the study area. About 32% of the forest roads of the study area are minor access or secondary roads that are categorised as class 4 (Table 7.3). About 59 km (19%) of the Stromlo Forest roads are major (primary) access roads, classified as class 3. Tracks are one of the main forest road types, of 66 km length and comprising 21% of the road network of the study area. Most tracks are used during timber harvesting, site preparation, plantation and urgent management activities like fire fighting. These are mostly dry weather roads and are classified as class 5. Public roads are sealed roads, comprising 13% of the forest road network of the study area, and are classified as class 1.

Table 7.3. Summary of the forest road classes of the study area; by classes actually used

Types of the roads	Road classes	Surveyed roads		All roads	
		km	%	km	%
Public Roads (Asphalt)	1	-	-	40	13
Public and Major Access	2 & 3	16	16	101	33
Minor Access	4	66	65	98	32
Tracks	5	20	20	66	21
Walking Tracks	6	-	-	2	0.7
Total	-	102	100	307	100

As shown in Table 7.3, all roads for which field data were gathered were selected randomly from the three road types (major, minor access and tracks). These are the main roads for operational purposes, and are used as feeder or connecting roads between compartments and public roads; most of them are unsealed roads. Erosion problems generally stem from improperly or incorrectly installed drainage structures, especially relief culverts on the roads located on steep terrain, and also from the lack of a maintenance program.

The extent of sealed class 2 roads was trivial, and these small sections of sealed road were distributed widely across the other class of the roads. It was not possible to segregate these small sealed segments, and their effect was assumed to be negligible.

Road Geometry

As described in Chapter 2, section 2.3.6, and Chapter 4, section 4.3.3, the geometry of the forest road surface is characterised as insloped, outsloped and crowned. Table 7.4 summarises the results of the road classification according to the type of road surface geometry assessed in the field survey. As shown in the table, about 57% and 60% of all and surveyed road lengths, respectively, were classified as having crowned geometry. About 16% and 27% of the Stromlo Forest road lengths were classified as having insloped and outsloped road surface, respectively, while these categories characterised about 13% and 27% of the surveyed roads.

Table 7.4. Summary of the forest road geometry of the study area

Road geometry	Surveyed roads		All roads	
	km	%	km	%
Crowned	176	57	176	57
Insloped	48	16	48	16
Outsloped	83	27	83	27
Total	307	100	307	100

Road Use

As described in Chapter 4, section 4.3.3, use of the forest roads of the study area was classified using the field survey data in conjunction with the ACT Forest road information.

Table 7.5 summarises the road use classification of the road network of the study area, and the surveyed roads. As shown in the table, most roads are classified as having either light and occasional or no traffic. Only 13% of the public roads are classified as having heavy or moderate traffic. Slightly more than 50% of the surveyed roads are classified as having no traffic and slightly less than 50% were classified as having light or occasional traffic. Most of the track roads are not used for a long period after timber harvesting and reforestation, except for emergency use (for example, fire fighting).

Table 7.5. Summary of use classes of forest roads of Stromlo study area

Road use	Surveyed roads		All roads	
	km	%	km	%
Heavy Traffic	-	-	36*	12
Moderate Traffic	-	-	4*	1
Light Traffic	21	21	72	23
Occasional Traffic	29	28	85	28
No Traffic	52	51	110	36
Total	102	100	307	100

*Public asphalt roads

Approximate Decadal Age

The age of forest roads plays an important role in forest road impact assessment processes. Thus, the forest roads of the study area were also classified according to the approximate decade in which they were built (1920s to 1980s), based on information supplied by ACT Forests. As the first forest road was built in 1926 (about 3 km) and the next in 1950, the first decade was called 'before 1950' (see Table 7.6). Class 1 or 'unknown' comprises public roads, and some tracks and minor access roads, which have no recorded documentation of the year of the construction. About 37% of the Stromlo Forest road network and 21% of the surveyed roads are classified in this group (Table 7.6). Only 1% of the roads were built before 1950. Almost 30% of the forest roads of the study area were built between 1950 and 1960. More than 32 percent (99 km) of all forest roads and 41% of the surveyed roads were constructed over two decades, between 1961 and 1980. Only 140 m of forest roads of the study were built after 1980, mostly in 1998.

Table 7.6. Summary of classification of the forest roads based on the year of building (in decades)

Forest Roads' Age (Decade) Classification					
Decades		Surveyed Roads		All Roads	
Class	Year	km	%	km	%
1	Unknown	21.5	21	3.02	1
2	Before 1950	0	0	91.08	29.7
3	1950 - 1960	30.5	30	57.82	18.8
4	1961 - 1970	39	38	41.5	13.5
5	1971 - 1980	11	11	0.14	0
6	1981 - 2000	0	0	307	100
Total	-	102	100	3.02	1

More than 99% of the roads in the study area were constructed more than 30 years ago. These roads, therefore, have become stable over time and for the reasons discussed previously in Chapters 2, 4, and 6, no substantial slope failures, landslides or any other relative road instability were found.

7.2.3 Road Slope Position Analysis

As described in Chapter 4, the road slope position has been identified as an important parameter for selecting the road segments for detailed survey and examining road-to-stream connectivity (Montgomery, 1994; Croke and Mockler, 2001; Wemple *et al.*, 2001; Hatfield, 2003; Takken *et al.*, 2005). As described in Chapter 4, section 4.4.2, the slope position of the forest roads was analysed using the approaches developed by Wemple *et al.* (2001) and Hatfield (2003). The results of slope position analysis of the study area, as a whole, were presented in Chapter 6.

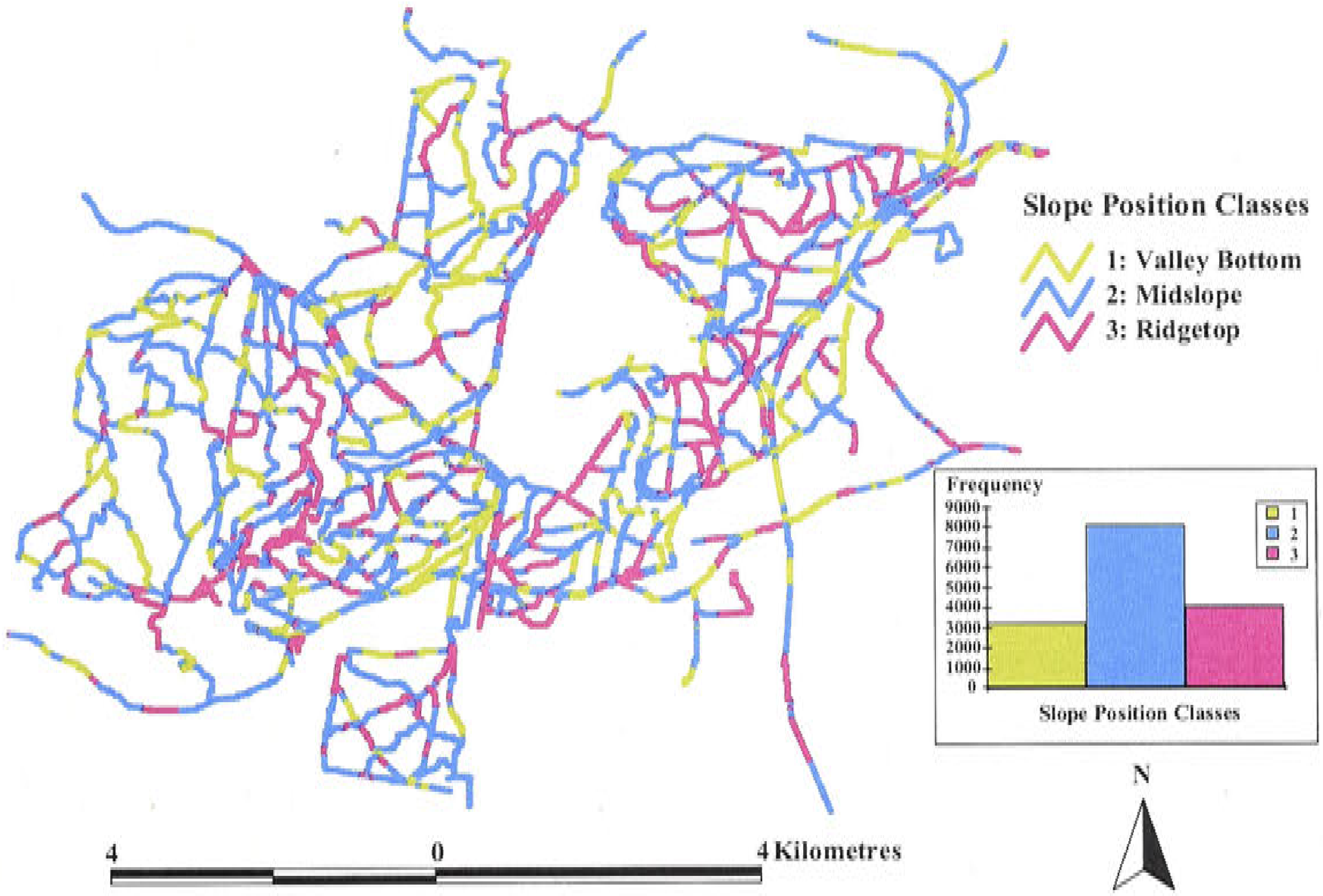


Figure 7.3. Slope position classes of Stromlo Forest road network

The forest road layer was intersected with the slope position layer of the study area using ArcGIS grid commands. Three thresholds (≤20, >20 - ≤80, and >80%), defined for reason described in Chapter 4, were used to classify the road network into valley bottom, midslope and ridgetop. Figure 7.3 illustrates the distribution of the forest roads among different slope position classes in the study area.

Table 7.7. Summary of slope position of the forest road of the study area

Slope position		Surveyed roads		All roads	
Classes	Name of Class	km	%	km	%
1	Valley Bottom	21	21	64	21
2	Midslope	54	53	162	53
3	Ridgetop	27	26	81	26
	Total	102	100	307	100

Table 7.7 summarises the slope position classes of all forest roads and surveyed roads of the study area. About 21% of both the Stromlo Forest road network and the surveyed roads

were located in valley bottoms. About 53% and 26% of the roads are located in midslope and ridgetop slope positions, respectively.

7.3 Hydrological Analysis

7.3.1 Watershed Delineation

GIS and DEM are generally used to perform watershed delineation to a point or an area of interest (Garbrecht and Martz, 1999; Lyon, 2003). The entire Stromlo Forest Management Area (SFMA) was delineated as a small catchment area using DEM analysis, in order to create basins, sub-catchments, sub-watersheds, and establish the exact ground positions of stream networks. The watershed was delineated using the basin and the hydrologic modelling extensions in ArcView, ArcInfo commands and TauDEM (Tarboton, 2004). The results of this process (basin, sub watershed and stream network layers) were used as input layers in all GIS modelling in this study, such as calculation of the hydrologic distance between roads and streams, road-to-stream connectivity, and slope position estimation.

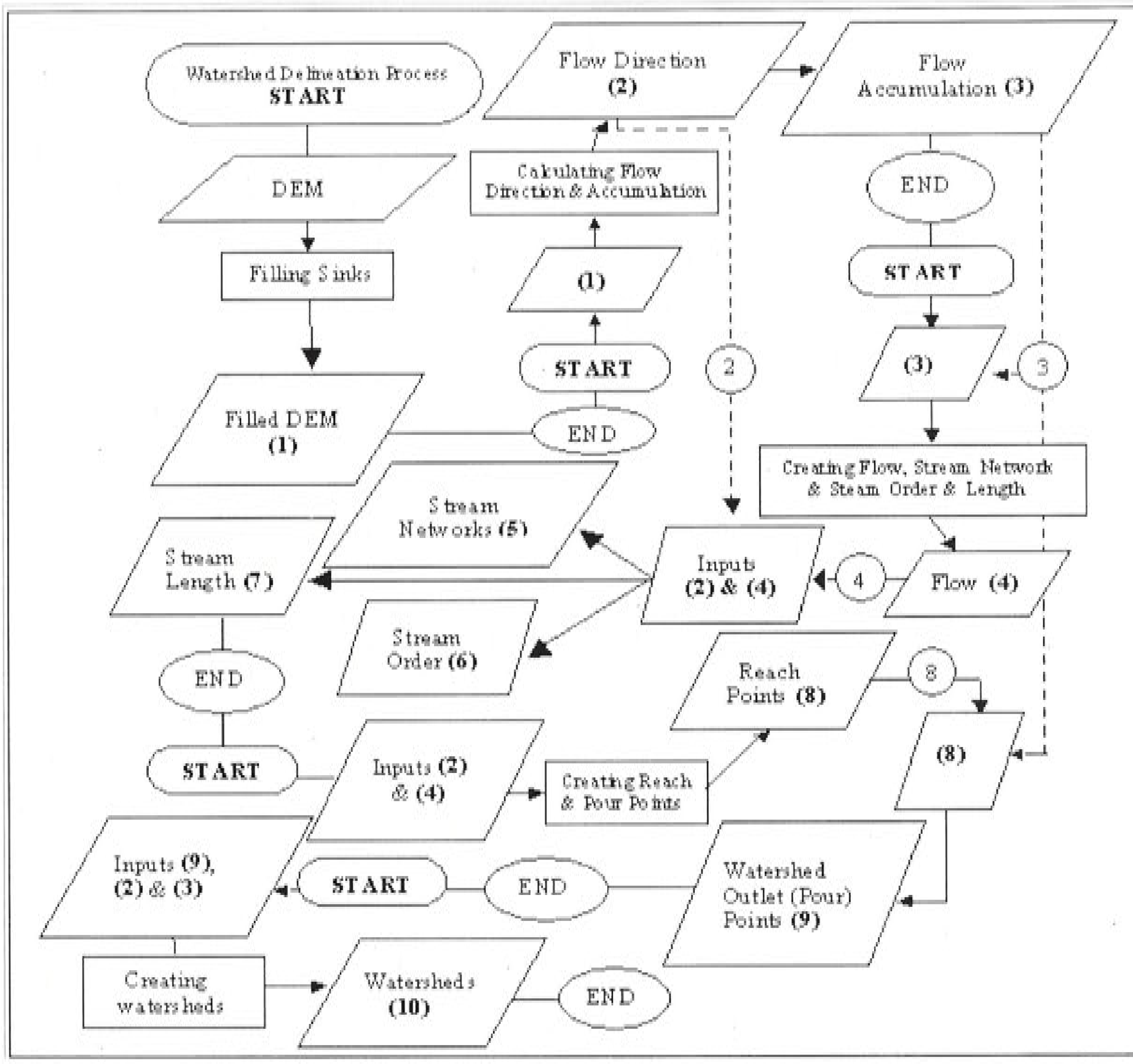


Figure 7.4. The hydrologic modelling and watershed delineation flow chart

Figure 7.4 illustrates the hydrologic modelling and watershed delineation processes as a GIS-based flow chart. The DEM of the study area (20 metres resolution) was used as an input layer. The first step is to fill in the sinks (areas which will not drain anywhere) in the elevation grid. Cells that appear not to drain anywhere may become a problem in the process of building a drainage network system that defines the flow path (Farabi, 2005). The next step was to create a flow direction network from the filled DEM. Flow accumulation is used to identify the downstream cells. These were used to create the stream network, stream order, stream length and points of reach. The watershed outlet (also called pour point) was created using flow grid and reach point inputs. Finally, this layer was used for creating the basin and watersheds (Figures 7.5 and 7.6). The watershed delineation process was also used to calculate watershed area, mean elevation, mean slope, stream flow length, and high and low positions of the stream.

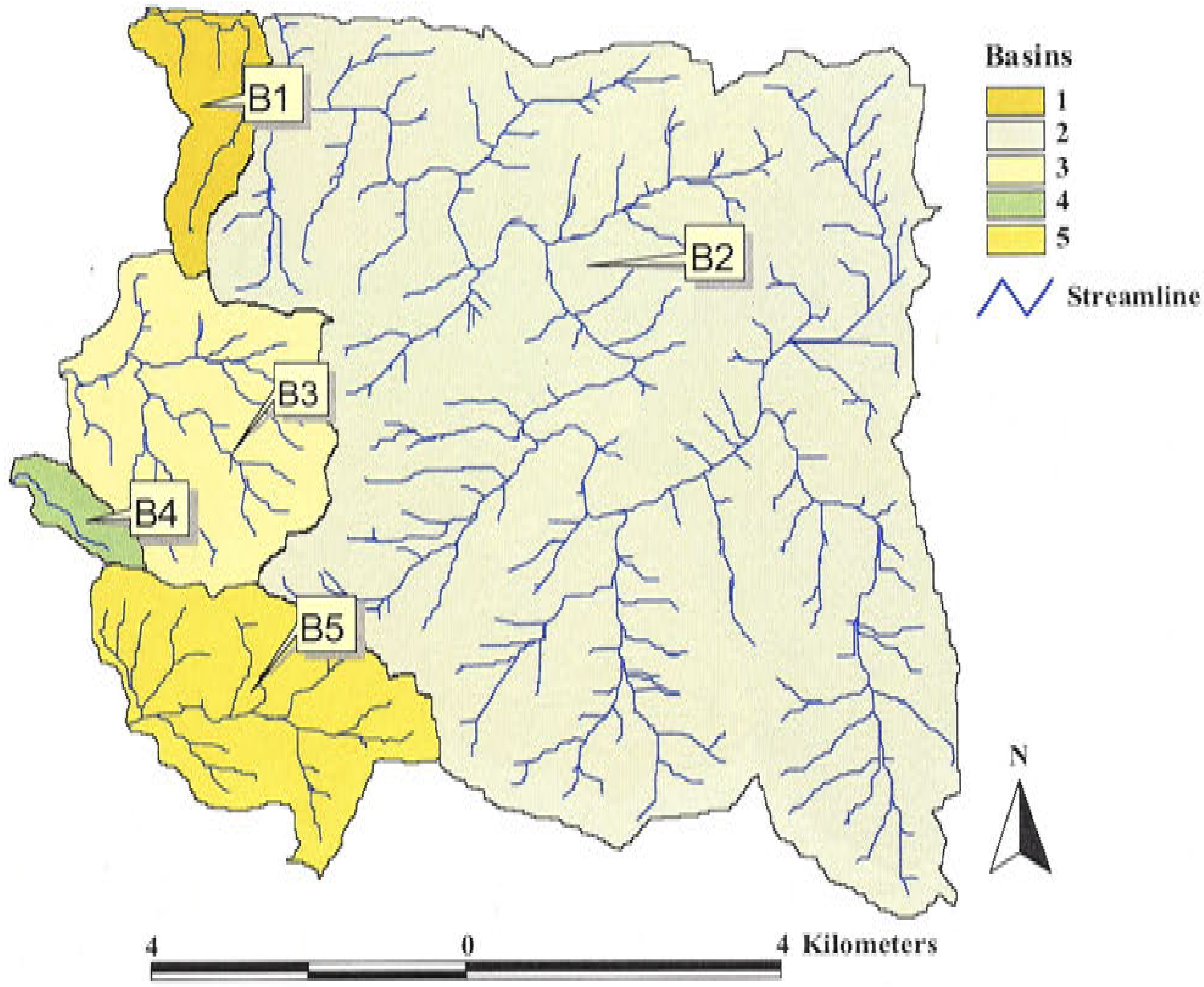


Figure 7.5. Basins of the study area

Table 7.8. Summary of the basin parameters of the study area

Basin ID	Area (ha)	Perimeter	Mean Elevation	Centroid Slope	Centroid X	Centroid Y
B1	327.4	11680	559	10	681027.5	6094347.5
B2	7992	54040	585	5	685917.5	6090167.5
B3	1073.3	17200	615	8	680997.5	6090717.5
B4	115	6640	586	7	679437.5	6089597.5
B5	969.3	18440	607	7	681837.5	6086897.5

Figure 7.5 shows the basins of the study area. This representation was created using ArcGIS 9, and ArcView 3.2a. The Arc and Grid commands, basin and hydrologic modelling extensions were used to create the basins. DEM and the stream network layer, created from the watershed delineation application, were used as input layers for the processes. Five basins were created based on the connectivity and continuous flow of the streams toward the end point of the basins (Figure 7.5). The basin parameters are summarised in Table 7.8. Basin number 2 (B2) is the largest, encompassing nearly 8000 ha covering more than 76% of the study area, while B4 is the smallest basin, at 115 ha (about 1% of the area).

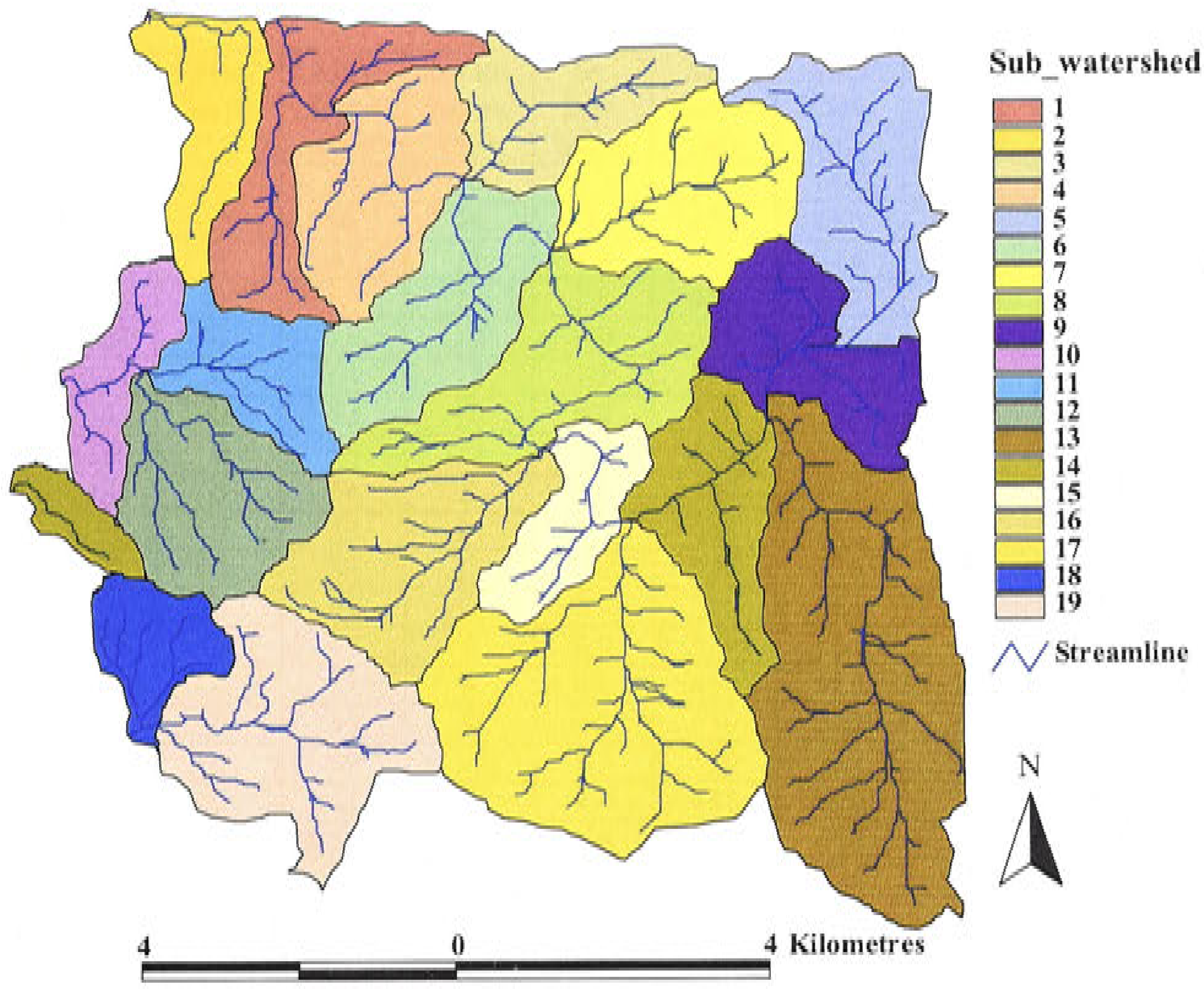


Figure 7.6. Sub-watersheds of the study area

Figure 7.6 illustrates the sub-watersheds of the study area. Watershed parameters are summarised in Table 7.9. Sub-watershed number 13 is the biggest among the 19 sub-watersheds, covering 1339 ha of the study area, while number 14 of 229 ha is the smallest sub-watershed. The minimum slope of the sub-watersheds is 0, while sub-watershed number 2 has a maximum slope value at 93%, the highest in the study area (Table 7.9). Sub-watershed number 16 has the highest maximum elevation value at 782 m above sea level while sub-watershed number 15 has the lowest maximum elevation value at 622 m.

Table 7.9. Summary of the sub-watershed parameters of the study area

ID	Area (ha)	Peri.* (m)	Min Slope (%)	Max Slope (%)	Mean Slope (%)	St. Dev. Slope	Min Elev.* (m)	Max Elev. (m)	Range Elev. (m)	Mean Elev. (m)	St. Dev. Elev.
1	481	14942	0	84	10	9.2	476	689	213	568	41.5
2	326	9724	0	93	14	10.4	455	686	231	559	44.7
3	377	9971	0	47	11	7.4	501	714	213	586	33.4
4	491	10116	0	63	11	7.8	489	672	183	560	36.3
5	564	14028	0	53	10	9.0	545	738	193	598	34.2
6	540	11371	0	64	12	7.1	501	748	247	571	43.3
7	576	360	0	52	10	6.6	510	735	225	594	31.9
8	683	14528	0	56	12	7.5	509	771	262	571	38.6
9	435	12486	0	64	8	8.6	539	672	133	574	24.6
10	250	8959	0	73	14	9.7	463	672	209	569	36.4
11	305	9269	0	58	12	7.4	520	776	256	616	41.4
12	519	9910	0	51	14	7.6	520	781	261	636	53.6
13	1339	18076	0	42	5	4.0	539	684	145	591	20.9
14	229	7268	0	53	9	6.6	484	684	200	573	27.7
15	279	8542	0	48	8	6.2	530	622	92	562	16.7
16	614	11879	0	59	11	8.5	530	782	252	627	50.8
17	1181	14611	0	41	6	4.0	535	690	155	596	25.0
18	550	10977	0	55	12	8.6	540	718	178	608	39.4
19	738	13509	0	43	7	6.0	550	723	173	607	31.8

*Peri. = Perimeter, Elev. = Elevation

Figure 7.7 shows the stream layers of the study area, in 5 different orders, resulting from implementing the watershed delineation processes using flow direction and flow accumulation commands in ArcGIS and ArcView.

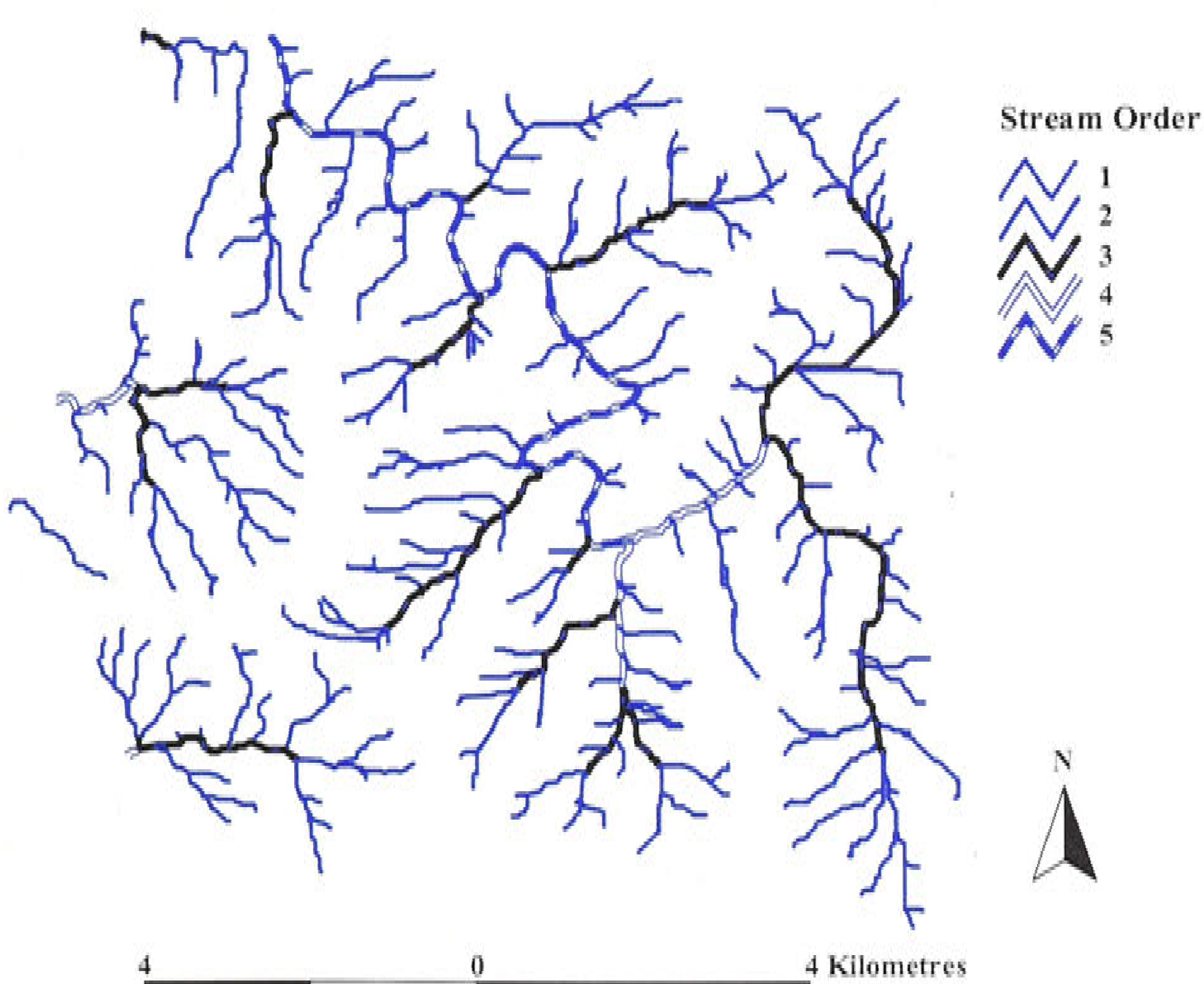


Figure 7.7. The stream layer of the study area

Figure 7.8 summarises the stream length of the study area by stream order. Total streamline length of the study area is nearly 218 km. First order streams have the greatest streamline in total among all the orders, at 116 km (53%), while the fourth order streams have the shortest length at about 6 km (3%). The main stream that drains most of the study area has a length of about 14 km (6%), while the lengths of stream orders 2 and 3 are about 54 km (25%) and 29 km (13%), respectively.

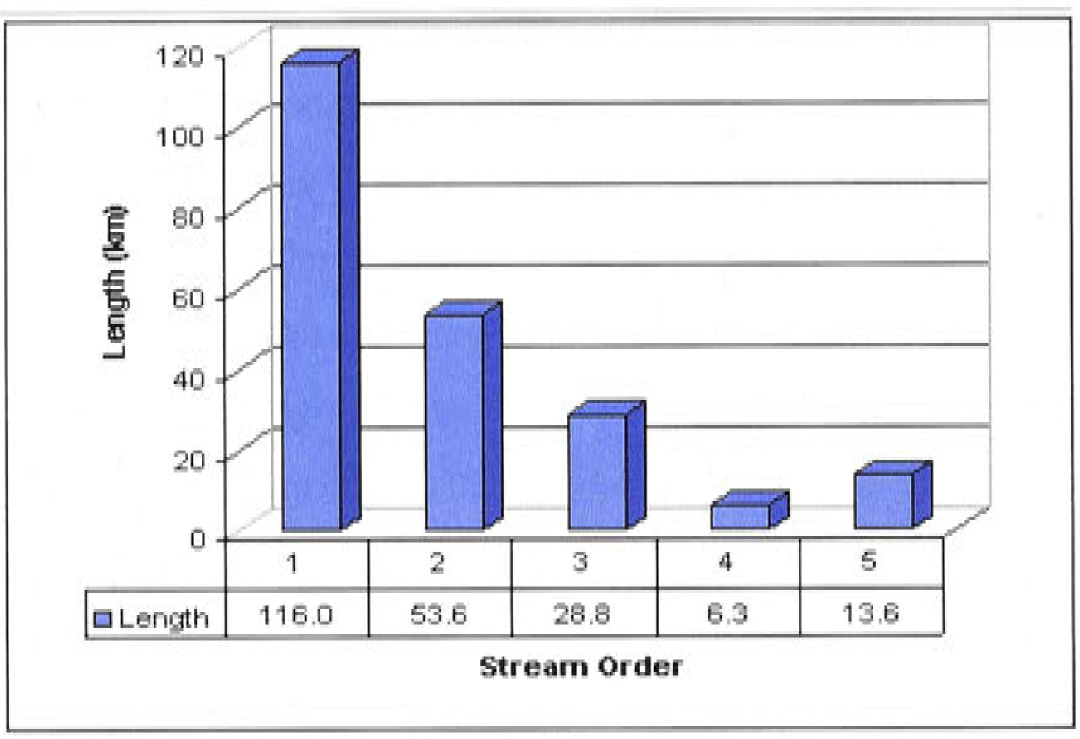


Figure 7.8. Stream length of the study area based on stream order

The streamline was topographically analysed using a surface extension (Jenness, 2005) in ArcView (3.2a) GIS software. The DEM layer was used for creating and extracting the surface and topographic characteristics of the stream. The elevation profile of the stream was then created to show the distribution of stream length based on the elevation. Each original streamline may have multiple segments; these were created to identify each segment within the original streamline. In total, the stream networks of the study area included 509 streamlines (main stream lines and segments). The longest length of a single streamline is 2021 metres, which represents the surface distance between the starting (high elevation) and the ending (low elevation) points. The shortest of the streamlines is 20 metres. The majority (78%) of the lengths of stream segments fall between 250 and 1000 metres.

Particular attention was paid to the watershed and stream delineation processes because the stream networks layer is one of the most important input layers in the calculation of the hydrologic distances between roads and stream.

7.3.2 Modelling Road-to-Stream Hydrologic Distance Using Five GIS-Based Models

The aim of the modelling processes discussed in this section was to predict which locations on a road would be most likely to connect and contribute sediment to streams. The method used was to calculate and model the flow path and length of runoff delivery from outlets of the road drainage structures to the streams (Farabi, 2005). This was done using ArcInfo commands and algorithms. The ArcInfo commands were written in Arc Macro Language (AML) using algorithms such as Particletrack and coding the function of water movement behaviour on the ground (Takken, 2003). The GIS-based model and application processes used in calculating the hydrologic distance are shown in Figure 7.9.

The stream coverage and stream grid were created from the existing stream network using ArcInfo, and these were then used as vector and raster input layers for model application. Two buffer zones at 5 and 10 metres width were created for the stream networks of the study area using ArcView and ArcGIS, and were used as input coverage layers for the application processes in the model. The recorded field data related to the road drainage structures and previously stored as multiple files, were used as drain point vector input layers. The ArcInfo *NEAR* method, *FLOWLINES, SFLINES FLOWPATH,* and *DISTWASH* models, and TauDEM extension for ArcGIS and MapWin, were used for predicting the hydrologic distance between roads and streams.

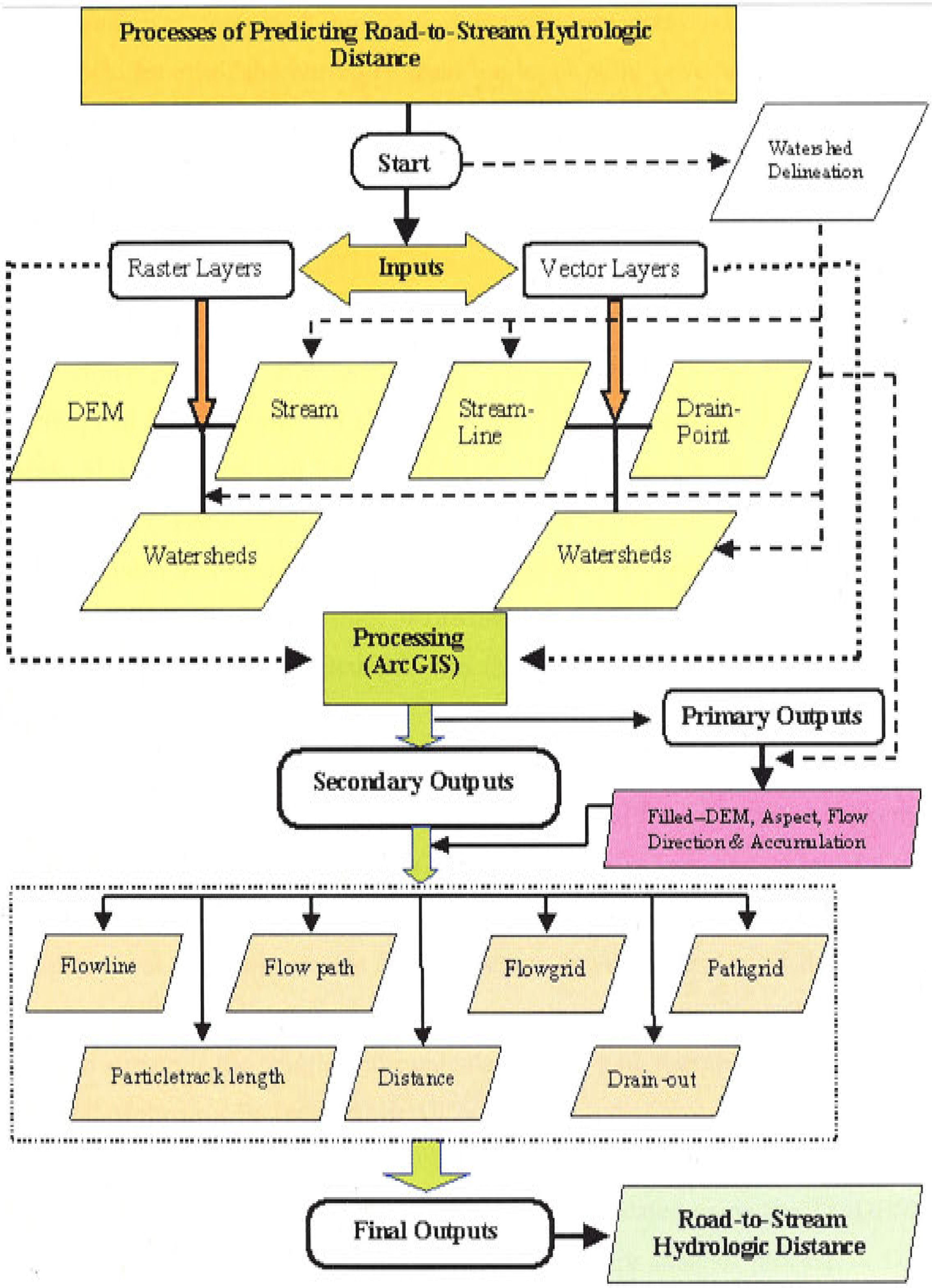


Figure 7.9. GIS-based model of road-to-stream hydrologic distance prediction

The ArcInfo *NEAR* method was used for determining the distance between the outlets of road drainage structures (points) and streams (lines). The Arc *NEAR* model determines the point-to-arc, point-to-node and point-to-point distances. The locations of the road drainage structures (point coverage) and stream network (line coverage) were used as input layers.

The distance was computed from each outlet drainage point to the nearest streamline. The output includes all of the attributes from the input point coverage, which is copied during the process, and the calculated distance that is added during the application. The *NEAR* application process, therefore, will not affect the input files and their coordinate precision (Farabi, 2005).

The *FLOWLINES* program is based on the particle-tracking algorithm known as 'Particletrack', and the grid function and code (Takken, 2003). This model predicts the direction and future location of a flow, based on the local velocity field by interpolating the nearest elevation grid cell centres (Farabi, 2005). The output of this model is a line coverage layer within flowlines. The flowlines start at the outlet of a drain and flow all the way down until they reach the edge of the grid (DEM) or join a streamline. These flowlines intersect with streamlines using *SFLINES* code (Takken, 2003). The output of these processes is a distance file that includes the length of flowlines from the outlets of the drains to the stream.

A *FLOWPATH* model is based on the grid function and flow direction (Takken, 2003). The model uses the flow direction grid to define the distance from the outlet of the drain to the stream. The model calculates the flowpath starting from the grid cell at the outlet of the road drain and then follows the flow direction down the grid until it reaches a grid cell (lowest elevation grid value) that has a streamline (Farabi, 2005). The distance between drain and stream is the length of the calculated flow path that was determined by the model at the end of the process (named GRIDPATH).

The road-to-stream hydrologic distance was also calculated using the TauDEM (Tarboton, 2004) extension for ArcGIS and WinMap by a network analysis process. A DEM grid file was used as input file and the distance was calculated using watershed delineation, network and DEM analysis (Farabi, 2005). The distance between each drain outlet and the closest stream was extracted from the grid output using ArcInfo commands and an AML (gridspot70.aml).

DISTWASH (Newham and Croke, 2002) predicts the road-to-stream hydrologic distance principally based on the grid function and flow direction using the watershed delineation process. The process of the hydrologic distance prediction in the *DISTWASH* model is almost the same as for most of the models, as mentioned above. DEM, flow direction, stream networks and watershed grid were used as input layers and the output layers comprised a grid file from which the distance data could be extracted using ArcInfo commands and gridspot70 macro, based on the location of the drains.

Figure 7.9 illustrates the overall processes of calculating the hydrologic distances between roads and streams; this involves most of the models in the flow chart. The input layers are almost the same for most models, especially when *FLOWLINES, SFLINES* and *FLOWPATH* models are used. However, predicting the hydrologic distance using MapWin and TauDEM requires the watershed of the study area as an input layer, as well as those layers used in other models.

All of the hydrologic distances calculated from the models were extracted using ArcGIS commands, and then compared with these distance measured in the field. Tables 7.10 and 7.11 summarise the results. Correlations between the calculated distances and distance measured in the field were determined using Pearson's simple correlation coefficients to identify highly correlated distances. The comparison shows that two models, *FLOWPATH* (GRIDPATH) and *FLOWLINES* (PTRA_LEN), predicted the distance more accurately than the others, based on correlation analysis (Figure 7.10, and Tables 7.10 and 7.11). Figure 7.10 is a correlation matrix between distance to stream as determined from the field measurement (FIELD_DIS) and five other potential indicators. As shown in Figure 7.10, GRIDPATH has the best correlation fit with distance measured in the field while PTRA_LEN has the second best fit among the others.

Table 7.10. Correlations (r) between field distance and distance predicted by different models

Models	FIELD_DIS	GRIDPATH	PTRA_LEN	DIST_MW4	DIST_WAS	DIST_NEA
FIELD_DIS*	1.00					
GRIDPATH	0.98	1.00				
PTRA_LEN	0.83	0.79	1.00			
DIST_MW4	0.44	0.40	0.50	1.00		
DIST_WAS	0.43	0.39	0.37	0.41	1.00	
DIST_NEA	0.12	0.11	0.12	0.21	0.11	1.00

*FIELD_DIS = Field Distance

The best predictor is clearly GRIDPATH (correlation coefficient r = 0.98, r^2 = 0.96 and p = 0.000) (Figure 7.10, and Tables 7.10 and 7.11). This was also the case in a previously reported preliminary analysis (Farabi, 2005; Appendix F). PTRA_LEN (Partricletrack length) predicts the next-best predicted distance compared with the field distance (correlation coefficient r = 0.83, r^2 = 0.69 and p = 0.000). Therefore, GRIDPATH and PTRA_LEN generate predicted distances that were highly correlated to the distance measured in the field.

Table 7.11. Comparison between road-to-stream hydrologic distance predicted by models and measured in the field

Predicted distance by models	R	R^2	Effect test	
			F Ratio	Pro.F
GRIDPATH	0.98	0.96	1295.9	0.000
PTRA_LEN	0.83	0.69	30.24	0.000
DIST_MW4	0.44	0.19	0.09	0.76
DIST_WAS	0.43	0.19	9.67	0.002
DIST_NEA	0.12	0.01	0.07	0.79

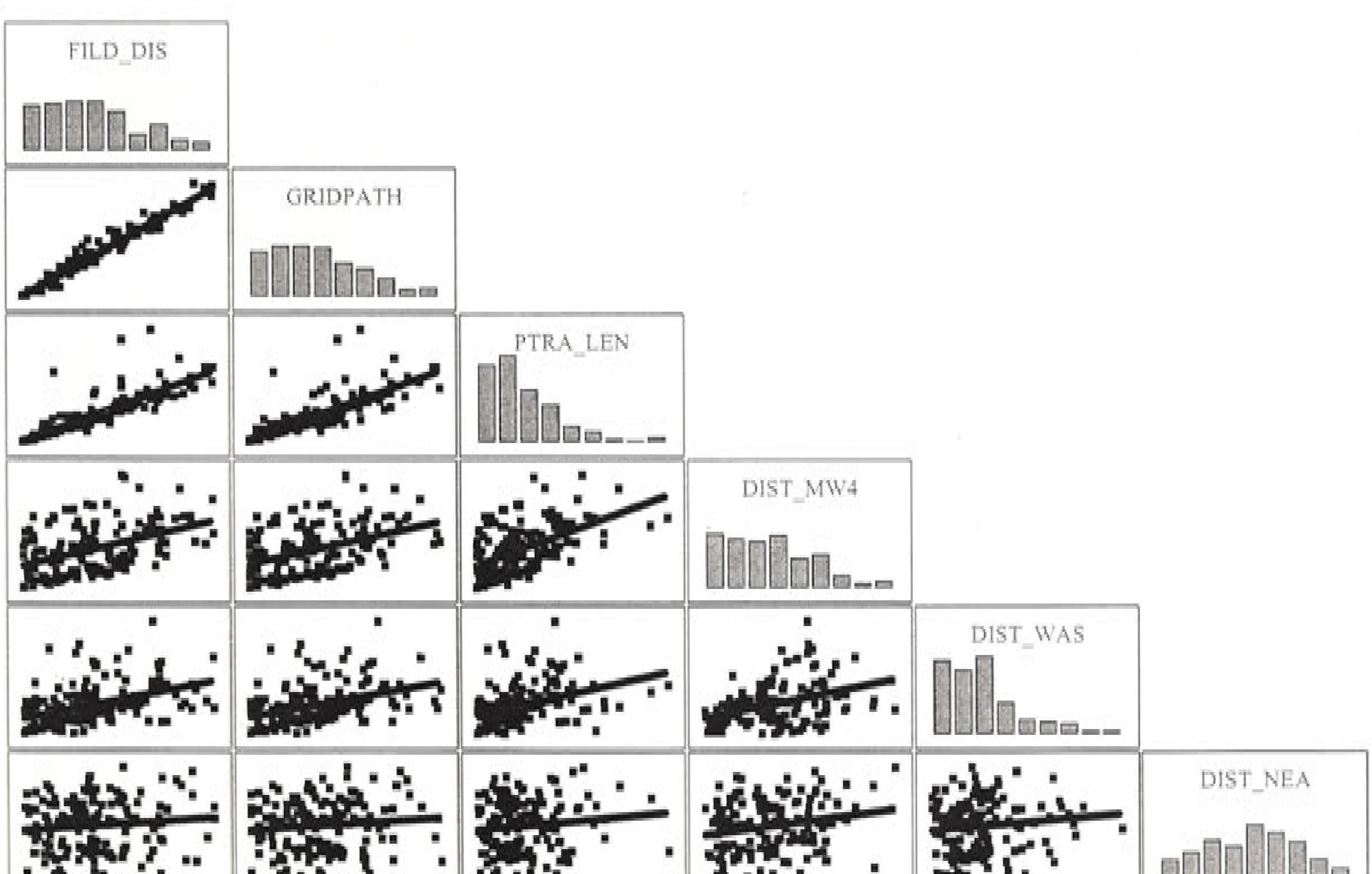


Figure 7.10. Scatter plots and histograms illustrating the relationship between road-to-stream hydrologic distance predicted by models and measured in the field

Figure 7.10 shows the correlation matrix and regression comparison of the hydrologic distance measured in the field with predicted distances. As can be seen in the figure, GRIDPATH and PTRA_LEN had the best fit with field distance. However, in the case of PTRA_LEN, while most predicted values were clustered close to the model line, a small number of values were scattered widely. Therefore, the distance predicted by *FLOWPATH* (GRIDPATH) model was used for the road-to-stream connectivity assessment because of its accuracy compared with other prediction methods.

Figure 7.11 illustrates the outcomes of *FLOWLINES, SFLINES* and FLOWPATH models. The flowlines start at the outlet of a drain and flow down and join a streamline. The flowpath starts from the grid cell at the outlet of the road drain and then follows the flow direction down the grid until it reaches a streamline.

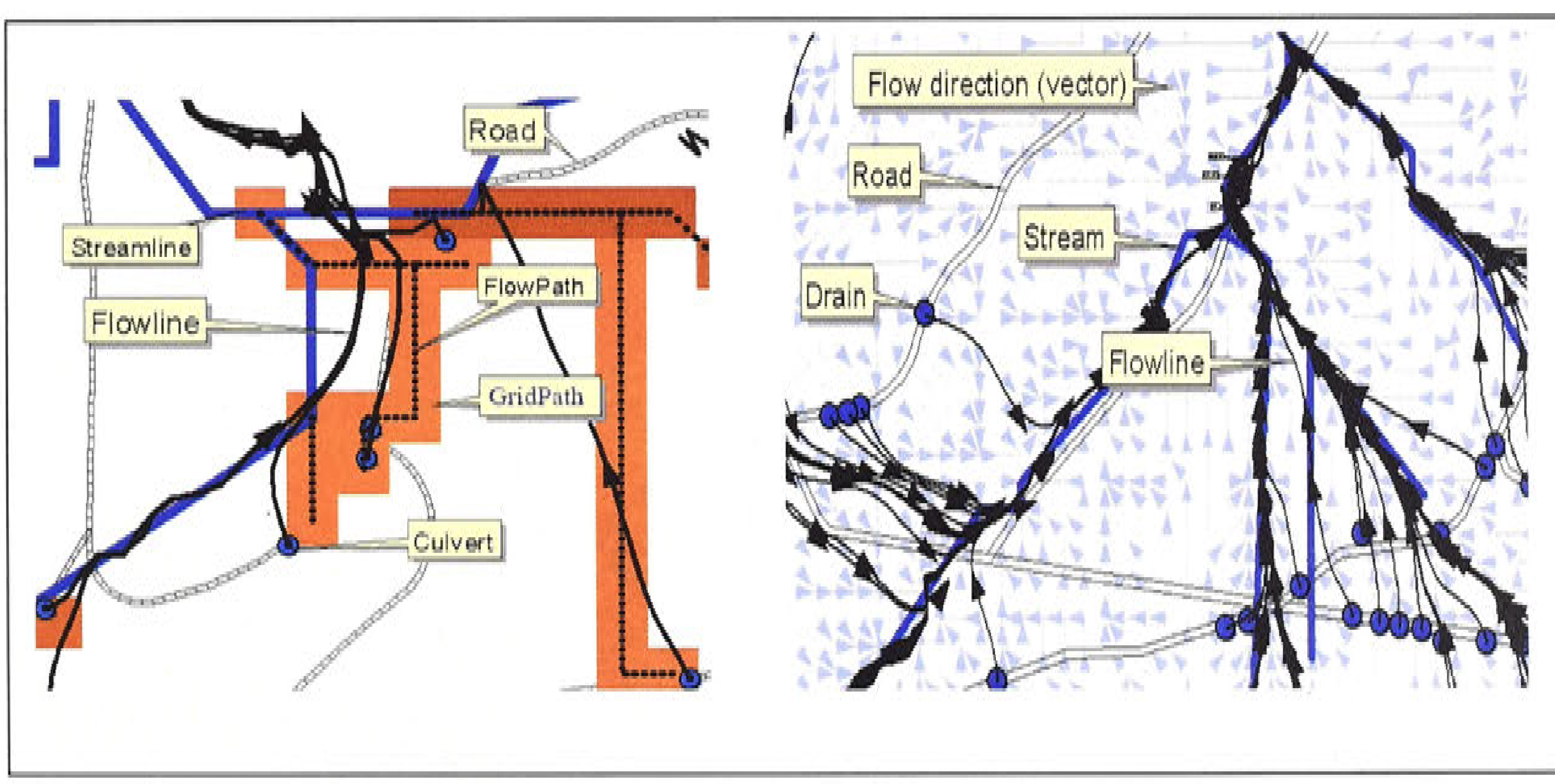


Figure 7.11. Flowlines calculated from the outlet of drainage structures to stream, and movement comparison among Flowpath, Gridpath and flowlines

A total of 254, 431 and 685 drainage structures from development, validation and field survey data sets, respectively, were used, separately, as input point coverage layers in the distance modelling process. The distance between a recorded drain and a streamline was calculated in order to use these measurements in road-to-stream connectivity assessment. However, in order to compare the results, find the 'bugs' in the programs and increase the accuracy, drains were split into separate files with a smaller number of drains and were then used as input layer for applying the models before final application using all drainage structures.

Addressing Problems with the FLOWLINES Model

One of the main problems that occurred during modelling was that some models, while generally making good predictions, predicted some situations quite erratically. For example, the *FLOWLINE* algorithm did not work accurately for some of the drain points. The predicted water pathway did not reach the stream properly in almost 5% of the points when a large number of drains (for example, more than 600) were used as the input for implementing the model. Some flowlines were correctly located from the outlet of the drains and the path to the stream was correctly simulated, but they did not join the stream grid cell correctly. As can be seen in Figure 7.12, the calculated flowlines followed an unrealistic and lengthy zigzag path along the streamline. However, the *FLOWLINES* model calculated the distance correctly for most drains.

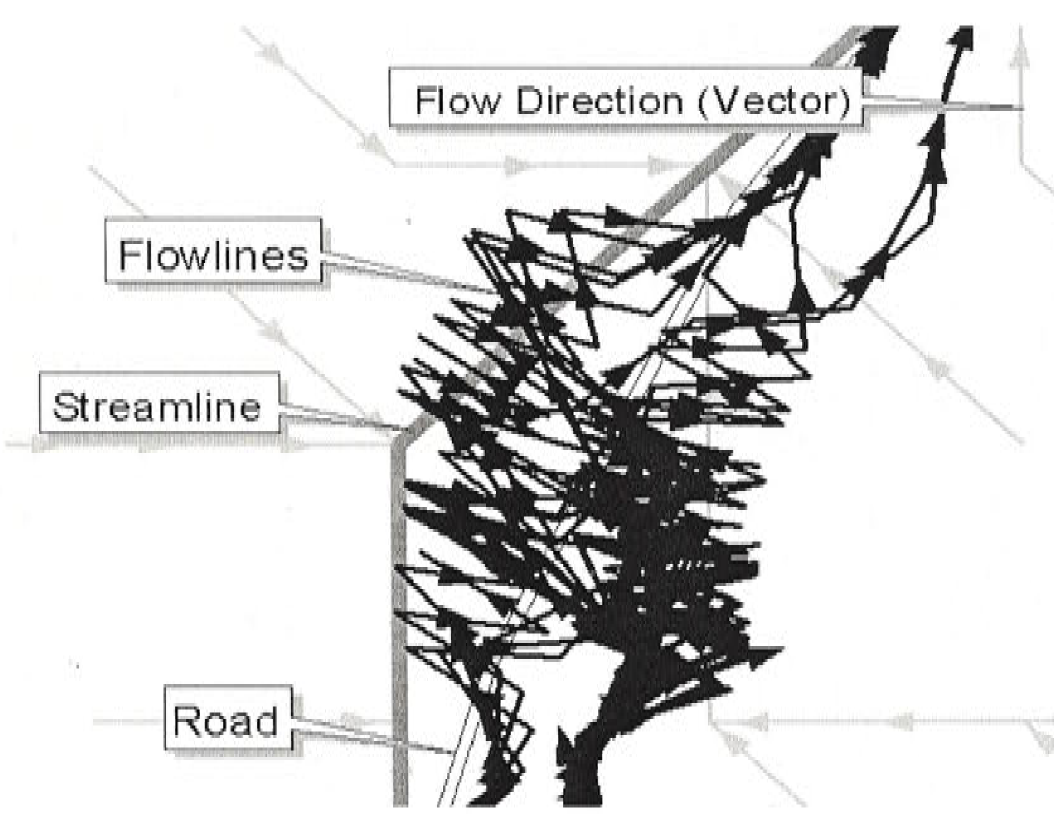


Figure 7.12. An example of erroneous predicted flowlines from the 'FLOWLINES' model

As mentioned previously, the model was applied many times with different numbers of input drainage points. It was found, first, that the model worked better with a smaller number of drainage points and, second, that the area of flat ground near the stream was the problematic area, where the models became 'confused' by the direction of flow and predicted water flowing backwards and forwards, thus exaggerating the length of flow.

The field observations of the drainage points where the model did not accurately predict the hydrologic distance showed that the width of the flat area was more than that of the defined stream buffer zone (5 m) for the model. The buffer zone is a distance back from the central streamline, at which point the model simply assumes that this is the end point, and that the flow will go straight to the stream. To solve this problem, the buffer zone was increased from 5 m to 10 m and then to 15 m. After this modification, the model handled the nearly-flat ground better, and erroneous predictions were dramatically reduced, to less than 2%. The problem was finally solved by repeating the application using the revised program and simulating a smaller number of drainage points. However, further revision and repetition with different numbers of drains would be needed to solve the problem completely.

7.3.3 Assessing Road-to-Stream Hydrologic Connectivity Using Statistical and GIS-Based Approaches

Modelling the level of road-to-stream water-flow connectivity is useful to help manage the impacts of runoff generated from the road prism. Although erosion and sediment production are inevitable adverse outcomes of road construction and maintenance, there will be no environmental impact on stream water quality unless roads and streams are connected by water-flow. Thus, it is important to know where the runoff will flow, where it may concentrate, and where it is most likely to connect to watercourses.

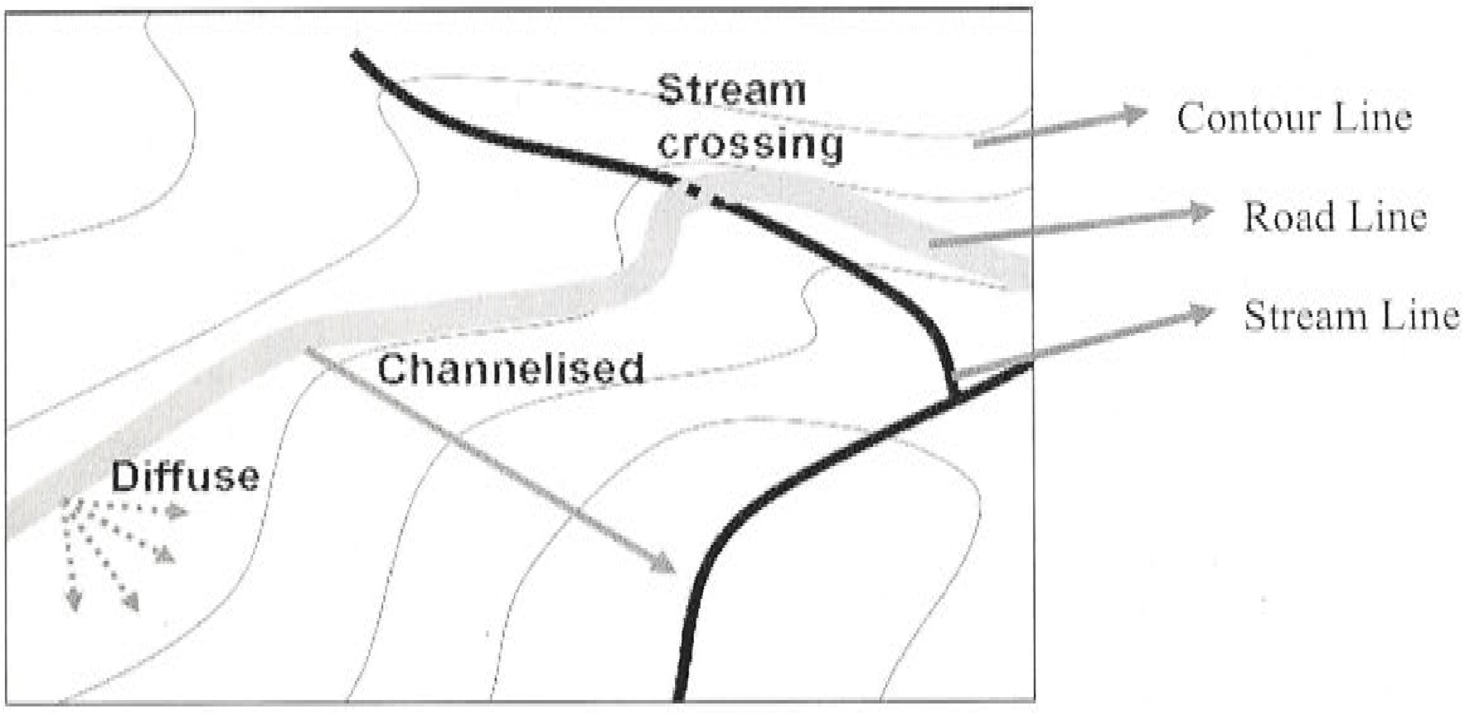


Figure 7.13. Road and stream connectivity based on type of sediment delivery pathway

Source: Takken *et al.* (2005:581)

The degree of connectivity between roads and streams was assessed using a method of classification of the different types of pathway delivery to streams presented in Takken *et al.* (2005). The road-to-stream connectivity is classified into three groups: stream crossing; channelised or gullied; and diffuse connections (Figure 7.13). In the first of these, at stream crossings, the runoff will be delivered directly to the stream. In the second, a channel or gully may continue from the outlet of the drain where it is initiated to the stream, and it may act as an extension of the stream network (Croke and Mockler, 2001 cited in Takken *et al.*, 2005). In the third, as can be seen in Figure 7.13, the runoff may reach or connect to the stream by diffuse overland flow in the absence of a stream crossing or channelised connection.

The probability of flow pathway and runoff originating from the forest road and reaching the adjacent stream through diffuse delivery pathways can be predicted using the 'vbt5' model introduced by Hairsine *et al.* (2002). Road contributing area (RCA), hillslope length (or the distance between the drain outlet and the stream) and slope gradient are the three variables used for predicting the probability of runoff reaching the stream in this model.

Road-to-Stream Connectivity Assessment Using a Fitted Threshold

Previous attempts to predict road-to-stream connectivity have included using a two-dimensional 'threshold curve', introduced by Croke and Mockler (2001), based on RCA and discharge hillslope gradients and the hydrologic distance between road drainage outlets and streams and discharge hillslope gradients. Croke and Mockler (2001) reported that their threshold curve (line) equation (RCA = 70 / sin (θ)) correctly predicted 94% of the observed gullies connectivity. Following this methodology, the hillslope gradient as measured in the field and the predicted hydrologic distances between roads and streams were used as input variables for connectivity prediction (Figure 7.14). The RCA was also used separately as input for predicting the gully and overland flow connection (Figure 7.15). The background information and related equations derived from these methods were described in section 4.6.2 (Chapter 4).

The results from using the threshold curve method show that these two factors can almost always correctly predict the hydrological connectivity between roads and streams (Figure 7.14). No connection was found between road drainage structures and streams when the hydrologic distance, using development data set, was more than 250 m, or where the hillslope gradient was less than 10%. The results of the statistical analysis show that there was a positive relationship between hydrologic distance and discharge hillslope gradient at the outlet of drains ($r = 0.77$, $r^2 = 0.59$, and $P < 0.0001$).

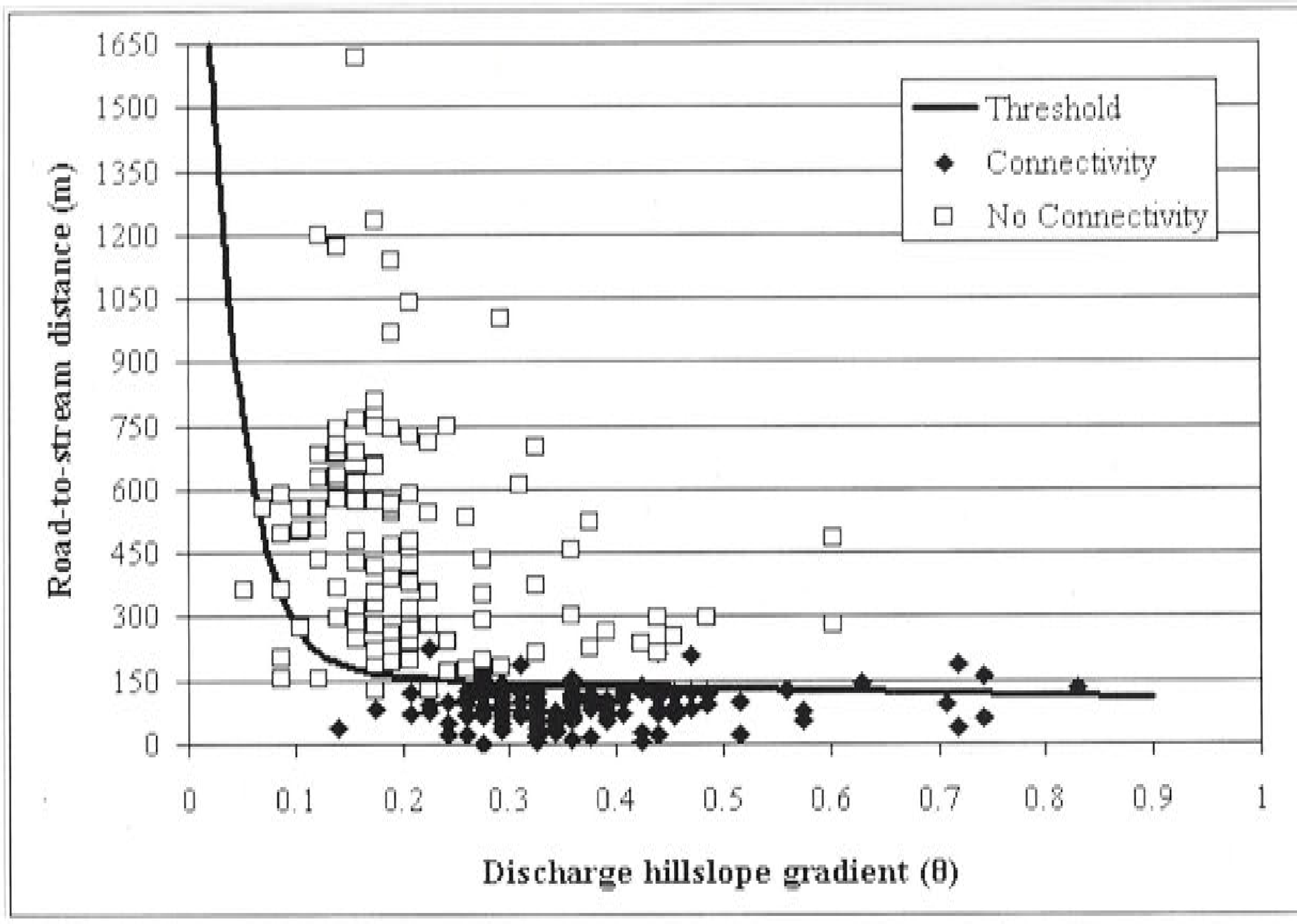


Figure 7.14. Fitted threshold curve using predicted hydrologic distance between road and stream versus hillslope gradient for drains surveyed from development data set

It is evident from Figure 7.14 and Table 7.12 that the hydrologic distance itself is not as important as its association with the degree of slope in road-to-stream connectivity analysis. For example, there is no evidence of connectivity between roads and streams where the distance of road-to-stream is more than 130 m when the hillslope gradient is less than 20% (Figure 7.14). However, at shorter distances, hydrologic distance is more relevant than slope gradient in connectivity between roads and streams. Almost all drains were connected to the streams where the distance was less than 50 m; hillslope gradient was not a relevant factor when the drains were located very close to the streams (for example, at stream crossing points). The analysis showed the hillslope gradient to be a significant factor in the connectivity between roads and streams where the associated distance is between 50 m and 250 m.

Classifying the Risk of Road-to-Stream Connectivity Arising From Hydrologic Distance and Hillslope Gradient

Table 7.12 summarises the risk of road-to-stream connectivity in Stromlo Forest associated with the hydrologic distance and hillslope gradient using the processes described in Chapters 4 and 6. The risk of road drainage outlet to stream connectivity is very low when the distance is more than 200 m and hillslope is less than 35%, when it is categorised as having negligible risk ranking. There is a low possibility of road-to-stream connectivity where the distance is between 200 and 150 m and hillslope is more than 30%. The risk of road-to-stream connectivity is moderate where the distance range is 150 - 100 m and hillslope is more than 25%. The risk of connectivity is high where the distance ranges between 100 and 60 m and hillslope gradient is greater than 20%, and extreme where the road-to-stream distance and hillslope gradient are less than 60 m and more than 10%, respectively (see Figure 7.14 and Table 7.12).

Table 7.12. Summary of the risk of road-to-stream connectivity using the hydrologic distance between roads and streams with associated hillslope gradient

Risk classes		Distance (m)	Associated hillslope gradient (%)
1	Negligible	>200	<35
2	Low	200 - >150	>30
3	Moderate	150 - >100	>25
4	High	100 - >60	>20
5	Extreme	<60	>10

Predicting Road-to-Stream Connectivity Using RCA and Hillslope Gradient

The two-dimensional threshold technique was also used to assess road-to-stream gully connectivity using RCA and hillslope gradient. As shown in Figure 7.15, the model predicts most instances of road-to-stream connectivity more accurately than that using hydrologic distance. This is probably because including RCA, a variable that indicates the volume of water in the flow pathway, introduces the concept of the amount of discharge as a causal effect on road-to-stream connectivity.

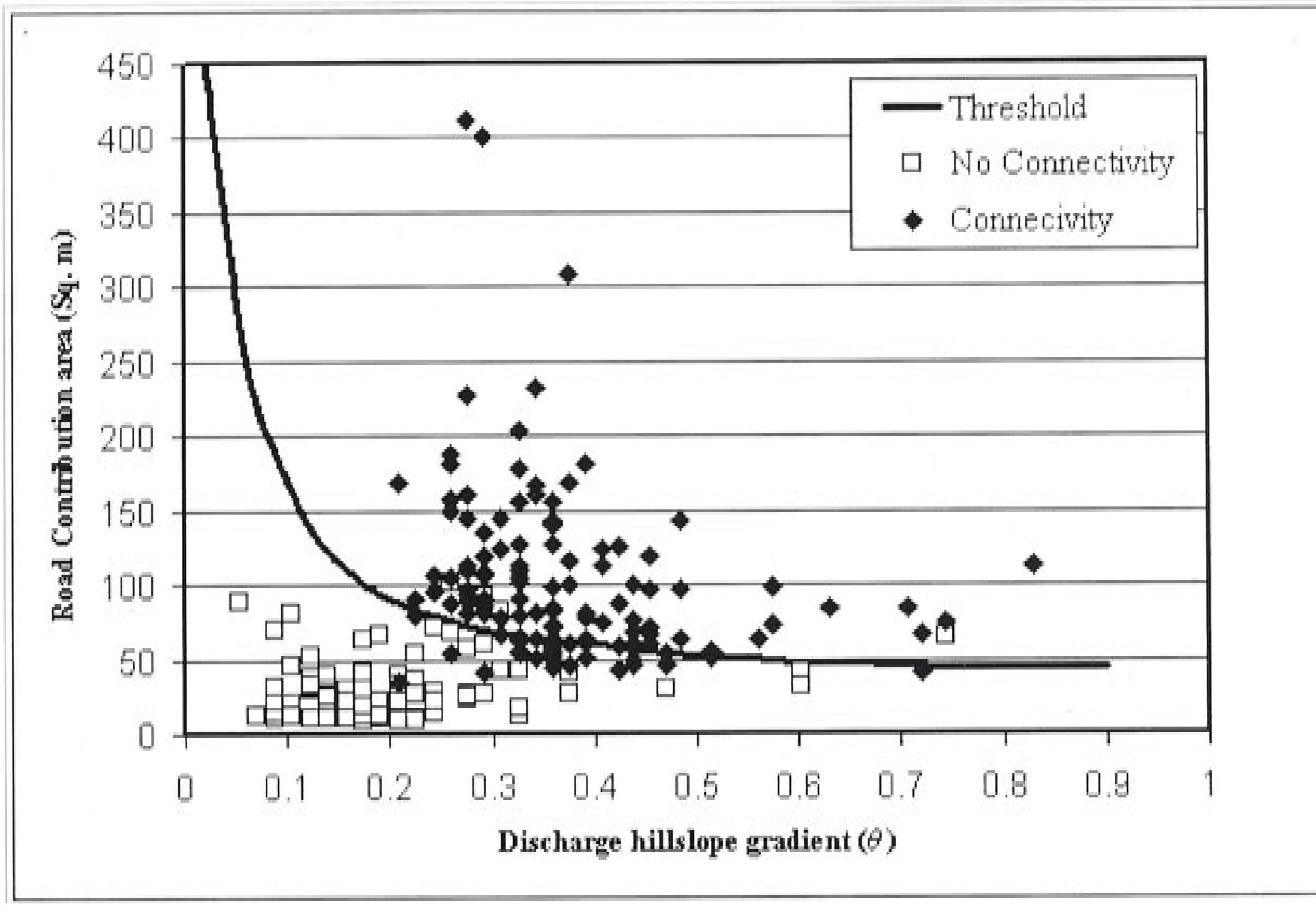


Figure 7.15. Fitted threshold curve using RCA versus hillslope gradient for drains surveyed

Figure 7.15 shows the road-to-stream connectivity using RCA and hillslope gradient for drainage structures surveyed from development data set. As can be seen in Figure 7.15, most drainage structures were linked to streams where the RCA and the hillslope gradient at the outlet of the drains were more than 70 m^2 and 30%, respectively. The figure clearly illustrates that almost all drains with a RCA higher than 100 m^2 and associated hillslope gradient of more than 20% were connected to streams.

Table 7.13. Summary of the risk of road-to-stream connectivity associated with RCA and hillslope gradient

Risk classes		RCA (m^2)	Associated slope gradient (%)
1	Negligible	<25	<35
2	Low	25 - <40	<35
3	Moderate	40 - <70	<30
4	High	70 - <120	>20
5	Extreme	>120	>15

Table 7.13 summarises the road-to-stream connectivity for drainage structures surveyed in the study area using the results presented in Figure 7.15. The risk of gully connectivity

between roads and streams is 'negligible' when RCA is less than 25 m^2 and associated slope gradient is less then 35%. There will be a small number of connections when the slope gradient is more than 40% and the RCA is less than 40 m^2; these are mostly related to the stream crossing points. There was always a connection between the outlets of road drainage structures and streams when the RCA and slope gradient value were more than 100 m^2 and 20%, respectively.

Most gully connectivity was located where the road contribution area, hydrologic distance, and hillslope gradient at the outlet of drains were greater than 100 m^2, 60 m and 30%, respectively. To extend and validate the results obtained by using the threshold, the same processes were applied to the validation data set to predict the road-to-stream connectivity. The results predicted gully connectivity when the contribution area was greater than 100 m^2 or the hillslope gradient was more than 30%.

A comparison of the results for road-to-stream connectivity predicted by threshold curves and those observed in the field shows that use of the threshold curve based on RCA predicts the road-to-stream connectivity slightly better than using the hydrologic distance or road contributing length used by Croke and Mockler (2001). The assessment shows that the threshold curve using RCA and hillslope gradient correctly predicted more than 96% of connectivity. However, the two-dimensional method was tested because it was an established and successful method. Considering the two variables simultaneously is useful for interpretative and illustrative purposes. However, in all cases where the predictive variables are considered in pairs (including using RCA, which was introduced here), there were always several outliers that were not well predicted. Predictions of road-to-stream connectivity were best when the logistic model described by equation 7.1 was used. Using this model seems to resolve the problem of outliers.

To predict the probability of diffuse connectivity between the outlet of the drains and streams, the volume of road-derived runoff reaching the streams (through overland flow) must be calculated. To do this, the 'Vbt5' model introduced by Hairsine *et al.* (2002) was applied to calculate and define the volume of runoff that would reach a stream from the outlet of a drain. According to Hairsine *et al.* (2002), the 'Vbt' is the volume of breakthrough, which is the volume of the runoff entering an area before a discharge is observed at the downslope boundary of that area. The 'Vbt5' is the volume of breakthrough for a 5-metre length of hillslope when the runoff volume is discharged from the drain (Croke *et al.*, 1999). The breakthrough volume (Vbt5) will generally be a combination of water lost to overland flow through infiltration, water stored in above-ground digressional storage, and water in transit between the upper and lower boundaries of the area (Hairsine *et al.* (2002). A steady-state infiltration rate of 11.7 mm/hr was used, based on its correspondence to the mean value during rainfall simulations on unsealed forest road surfaces (Croke *et al.*, forthcoming; Takken *et al.*, 2005).

Rainfall with a 10-year recurrence interval of 30 minutes duration and 50 mm/hr intensity was simulated for the study area (see also Chapter 3, section 3.4.3) in order to derive one of the factors in calculating Vbt. The volume of the runoff collected by each road drainage structure was calculated using the infiltration rate for the unsealed forest roads, the rainfall, and RCA. The Vbt5 model was applied using hillslope gradient, RCA, and the predicted distance between roads and streams as input layers.

The intersection application available in ArcGIS and ArcView was used to find the stream crossing points. The surveyed forest road layer and the stream layer of the study area were intersected to created the stream crossing point layer. These points were then compared with direct connectivity observed in the field to verify the prediction. The results are presented in Table 7.14.

Table 7.14. Summary of the types of connectivity pathways of the study area

Types of connectivity	Drainage structures surveyed					
	Development set		Validation set		Field survey set	
	N	%	N	%	N	%
Stream crossings	19	7	31	7	50	7
Gully	63	25	120	28	183	27
Diffuse connection	56	22	89	21	145	21
No connection	116	46	191	44	307	45
Total	254	100	431	100	685	100

Table 7.14 summarises the type of the road-to-stream connectivity pathways of the study area. The results show that about 54%, 56% and 55% of drainage structures from development, validation and field survey data sets, respectively, were connected to the

streams either by stream crossing, gully, or diffuse connection. No type of connection was found for nearly 45% of drainage structures from all data sets.

As shown in Table 7.14, about 7% of the drainage structures surveyed in the field drained directly to a stream at a stream crossing; these were mostly culverts. Gully connections were more widely distributed over the SFMA; these were about 27% of the drainage structures from the field survey data set, and about 25% and 28% of the drainage structures surveyed in the development and validation data sets, respectively. The majority of gully connections were found along roads adjacent to Mount Stromlo. All other drains, especially those on the lower parts of the road in the valley bottoms, were connected through diffuse overland flow because of their close proximity to the streams along the Molonglo River. In addition, field observations revealed that most road-to-stream connectivity was diffuse overland flow where the distance was less than 30 m, and that the road-to-stream connectivity occurred by diffuse overland flow, instead of gully or channelled connectivity, where the hydrologic distance was more than 150 m.

Road-to-Stream Connectivity Model Development

The same analytical approaches described for the road surface and outlet of drainage structures in Chapter 6, section 6.4.1 were implemented to model the relationship between all independent variables listed in Table 6.16 (Chapter 6) and road-to-stream connectivity. Logistic relationships between road-to-stream connectivity parameters and the independent variables were fitted using a forward stepwise procedure.

The best logistic model to classify road-to-stream connectivity (equation 7.1) included the RCA, hillslope, USCA and hydrologic distance between roads and streams as significant parameters ($p<0.0001$), and correctly classified over 97% of the observed presence and absence of rills or gullies (Table 7.15). There is no evidence of a lack of fit (Hosmer and Lemeshow $\chi^2 = 4.28$, $p>0.83$). Further details of the model fitting and testing are presented in Appendix D. The overall logistic model for road-to-stream connectivity, based on equation 4.11 and the estimated parameters presented in Appendix D, Table 17, is:

$$Y_i = -12.59 + 0.052 * RCA_i + 0.498 * HSG_i + 0.01 * USCA_i + (-0.007 * Dist_i) \quad (7.1)$$
$$[3.436] \quad [0.018] \quad [0.158] \quad [0.005] \quad [0.002]$$

where [] denotes standard error;
Y_i denotes odds of road-to-stream connectivity i;
RCA_i denotes Road Contributing Area i;
HSG_i denotes hillslope gradient in i percent;
$USCA_i$ denotes Upslope Contributing Area i;
$Dist_i$ denotes road-to-stream hydrologic distance i.

Table 7.15. Classification table of results of road-to-stream connectivity prediction

Road-to-Stream Connectivity	Road-to-Stream Connectivity Prediction		
	False ($P_i < 0.50$)*	True ($P_i \geq 0.50$)	Correct prediction (%)
Not observed	110	5	95.7
Observed	2	137	98.6

* $P_i = 1/[1 + \exp(-Y_i)]$

The classification table (Table 7.15) is often used to indicate the classification testing of the logistic regression model. The 'percentage correct' generally relates to sensitivity and specificity (or the reverse); the result here shows that more than 97% of the road-to-stream connectivity is correctly predicted by the model.

Model Validation

The same processes as described in Chapter 6, section 6.4.2, for erosion from the road surface and outlets of the drainage structures, were applied to validate the logistic developed model for road-to-stream connectivity (equation 7.1). The independent validation data set, as described in Chapter 6, section 6.4, was used to validate the logistic model (equation 7.1) developed for predicting the probability of the road-to-stream connectivity occurrence. The presence or absence of road-to-stream connectivity for these data was estimated using the fitted logistic function (equation 7.1) and found to match the observed condition on 97% of occasions (Figure 7.16). The 3% of cases where equation 7.1 did not result in a correct classification of road-to-stream connectivity were limited to those conditions where the probability predicted by the equation was between 0.39 and 0.65. That is, there was total agreement between the model and the observations when the outcomes predicted by the model were less than 0.40 or greater than 0.65. Although this range is greater than that presented in Figures 6.11 and 6.12, the actual number of miss-predictions is very low. This indicates that equation 7.1 is a valid and useful model.

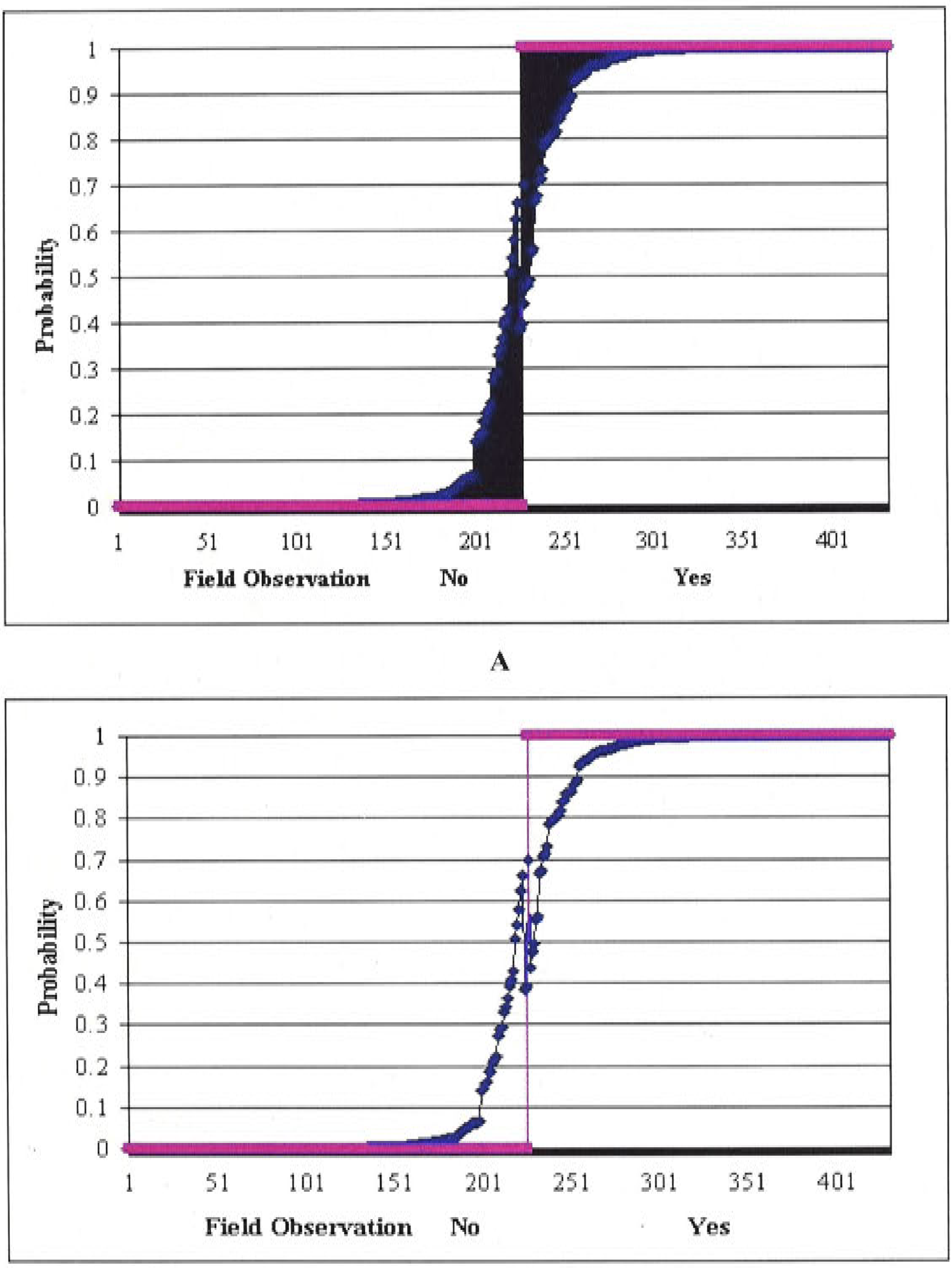


Figure 7.16. Probability of road-to-connectivity predicted by the model versus field observation. A: Scattered distribution. B: Nonlinear distribution showing discontinuity when predictions were incorrect

The overall result of testing this model strongly validates the model created using the development data set. This also shows that road contributing area, hillslope gradient, upslope contributing area and the hydrologic distance between roads and streams are the most important predictors of road-to-stream connectivity occurrence.

7.4 Mapping Road-to-Stream Connectivity Risk

As mentioned previously in this Chapter and in Chapters 4 and 6, the road-to-stream hydrologic distance is an important risk predictor variable in road-to-stream connectivity assessment. The risk of this connection occurring was mapped using the hydrologic distance and the results presented above. The connectivity risk was also mapped using all significant variables influencing road-to-stream hydrologic connectivity presented in the road-to-stream connectivity model (equation 7.1). Although the process of determining the risk of road-to-stream connectivity and possible sediment delivery through overland flow pathway (diffused) and gullied connection is not simple, it can be facilitated using a GIS-based method. To map the risk of road-to-stream connectivity based on road-to-stream hydrologic distance, buffers of different widths (60, 100, 150, 200 and 250 m) were created around the streamline layer using ArcGIS and ArcView. The forest road layer was then overlayed and intersected with the buffer maps (see Figure 7.20). The roads were classified based on the distance between roads and streams, and the risk ranking presented in Table 7.13. The processes can also be implimented using the MCE method provided in GIS software (for example, IDRISI). Figure 7.17 illustrates the overlaying of different buffer layers around streams to evaluate the risk of road-to-stream connectivity.

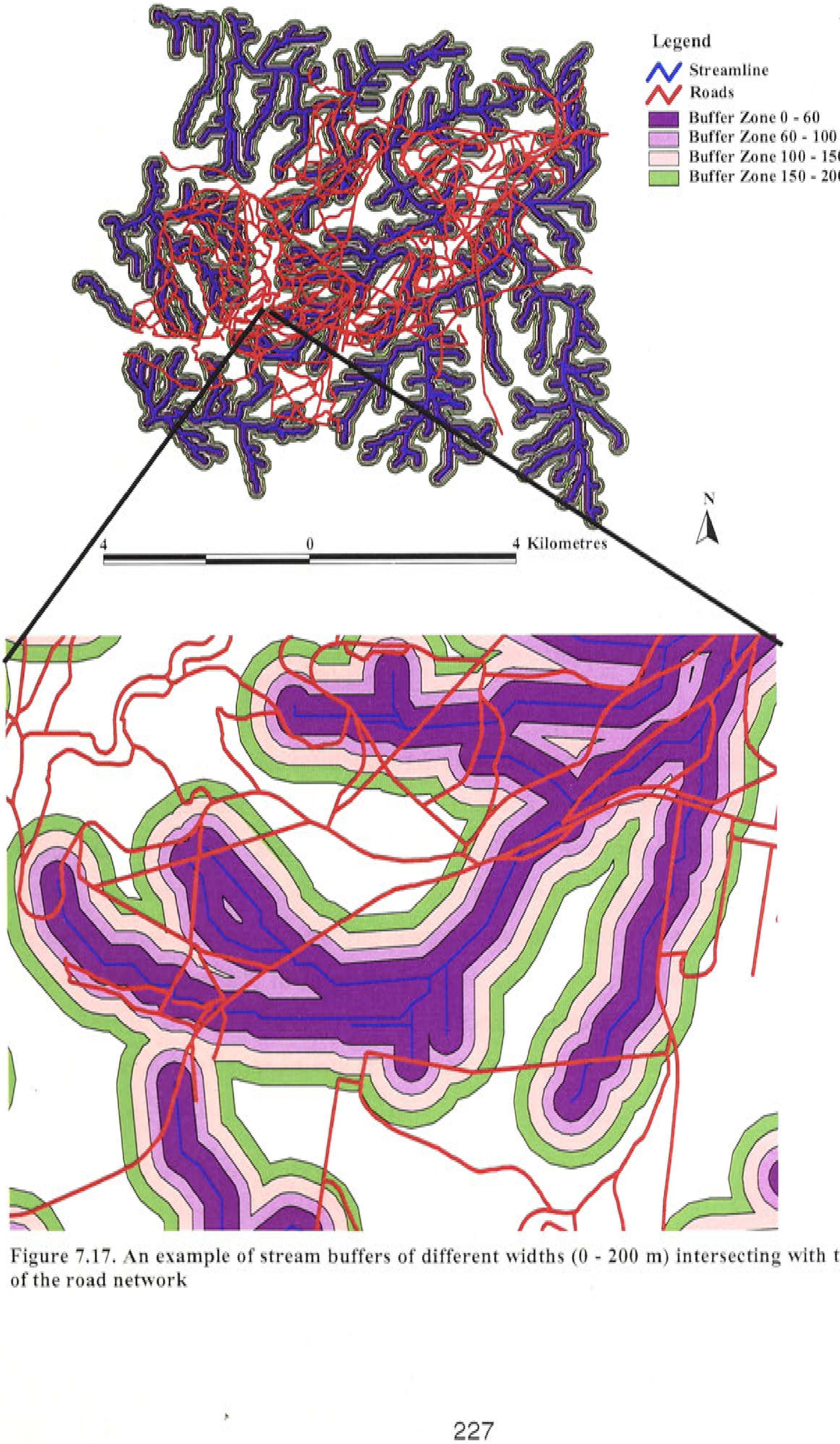


Figure 7.17. An example of stream buffers of different widths (0 - 200 m) intersecting with the position of the road network

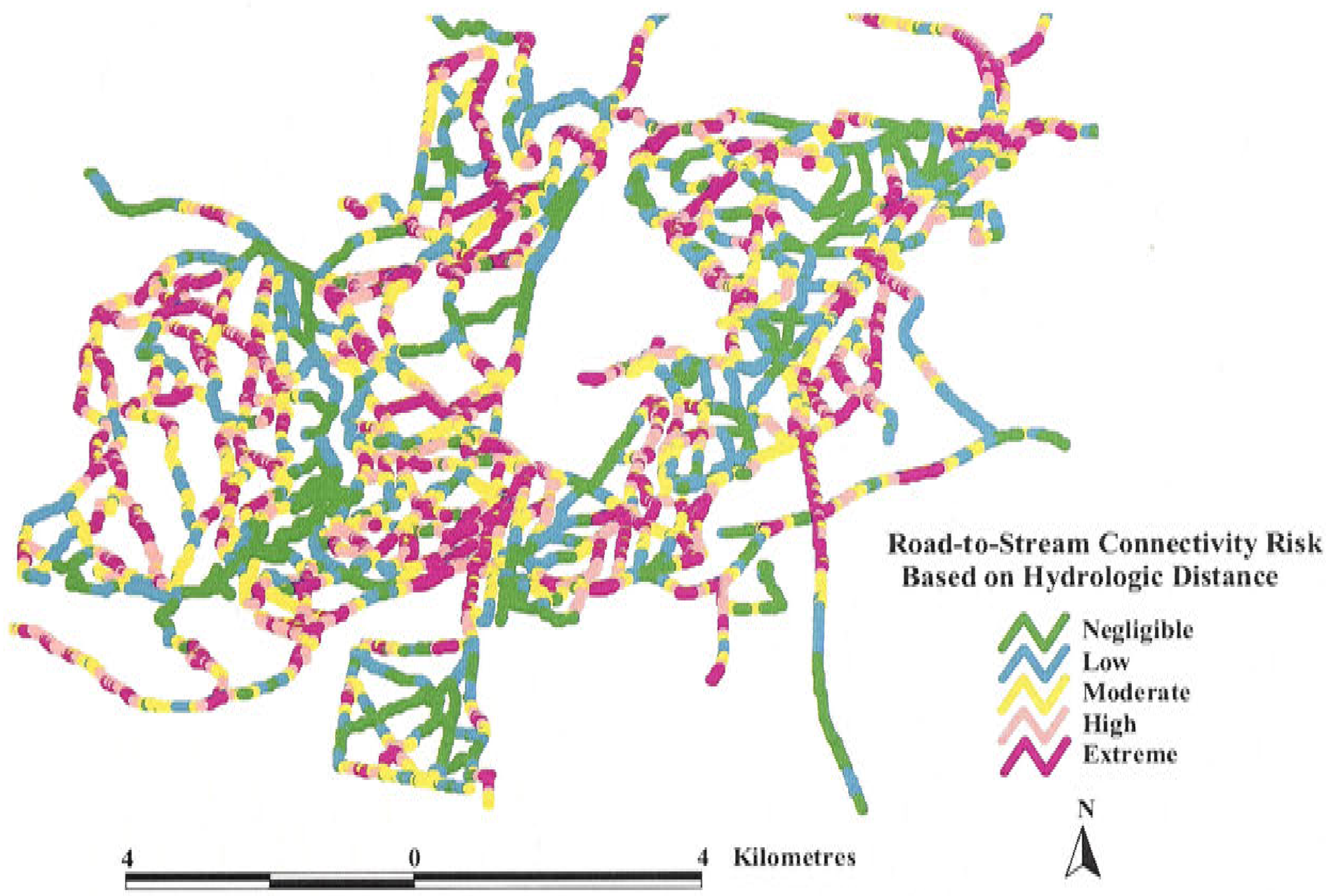


Figure 7.18. The risk map of the road-to-stream connectivity based on the hydrologic distance to streams for the Stromlo Forest road network

Table 7.16 summarises the results of risk classification of the road-to-stream connectivity for forest road network of the study area. This risk assessment is mapped in Figure 7.18. About 32% (98 km) and 35% (36 km) of the road network and surveyed roads, respectively, were located more than 200 m from the streams, and were classified as having 'negligible' risk of connectivity. The distance of almost half of the public roads of the study area was more than 200 m from the streams, and was therefore classified in this group. About 38% of all road network and 35% of surveyed roads were classified as having 'high' or 'extreme' risk of connectivity, indicating that the forest roads were built close to the watercourses (that is, less than 100 m).

Table 7.16. Summary of the roads at risk in terms of the road-to-stream connectivity using the hydrologic distance

Risk classes	Surveyed roads		All roads	
	km	%	km	%
Negligible	36	35	98	32
Low	19	19	53	17
Moderate	11	11	41	13
High	15	15	48	16
Extreme	21	20	67	22
Total	102	100	307	100

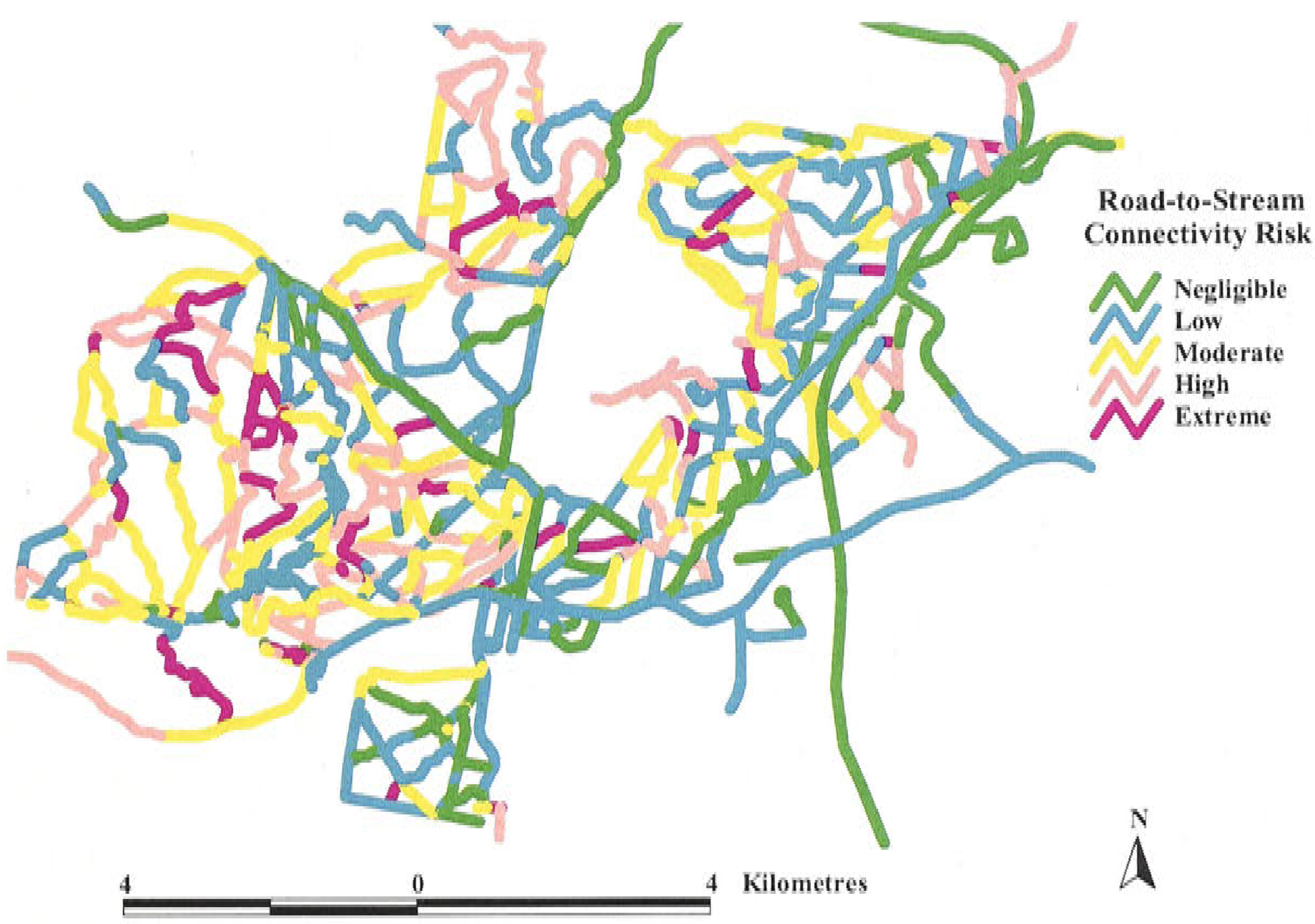


Figure 7.19. The risk map of the road-to-stream connectivity based on all variables influencing the road-to-stream connectivity occurrence

Figure 7.19 illustrates the risk of road-to-stream connectivity occurrence using all variables influencing the risk of the connectivity (that is, hillslope gradient, RCA, USCA, and road-to-stream hydrologic distance). As described in section 6.5 (Chapter 6), the risk was first ranked for the sampled road segments according to the variables assessed as significant risk factors influencing the connectivity risk in the model development, testing and validation processes, and road-to-stream connectivity assessment using the threshold curves. This was generalised to create the risk map for all road segments of the study area. According to

British Columbia Environment (1995a), Ryan *et al.* (1998), Australian Government (2000), Villeponteaux and Elder (2000), Macdonald *et al.* (2001) and Croke and Mockler (2001), the likelihood of road-to-stream connectivity is high when the hillslope gradient and RCA values at the outlet of road drainage structure are high and the road is located close to streamline (that is, less than 100 m). Under these conditions, roads would be at high and extreme risk in terms of connectivity and delivering sediment to streams (British Columbia Environment, 1995a; Ryan *et al.*, 1998).

For example, the likelihood of road-to-stream connectivity would be between 'possible' (level 3) and 'almost certain' (level 5) when the road is located closer than 100 m to a stream and hillslope gradient at the outlets of drainage structures is more than 30%. In this situation, the consequences of road-to-stream connectivity would be between 'moderate' (level 3) and 'catastrophic' (level 5). The scores associated with these levels of likelihood and consequences would be between 9 - 25, and the risk levels associated with these scores are 'moderate' and 'extreme', respectively. The greater the RCA and USCA, the greater the volume of runoff discharge from the outlet of drains and the higher the flow towards the stream; this may cause high erosion rates, increase the possibility of rill and gully occurrence on the road surface and sediment movement from the road surface and outlet of drainage structure down into an adjacent stream. No road-to-stream gully connectivity was found when USCA was less than 90 m^2 and hillslope gradient was less than 10%. Gully connectivity was found when the USCA and RCA were more than 5000 and 100 m^2, respectively. Croke and Mockler (2001) stated that there is a high possibility of road-to-stream gully connectivity when the RCL and RCA values are more than 25 m and 70 m^2, respectively.

Table 7.17. Summary of the road-to-stream connectivity risk for the study area

Risk classes	Surveyed roads		All roads	
	km	%	km	%
Negligible	26	25	64	21
Low	30	29	92	30
Moderate	20	20	74	24
High	16	16	56	18
Extreme	10	10	21	7
Total	102	100	307	100

Table 7.17 summarises the road-to-stream connectivity risk according to the combined effects of the variables influencing the risk of the connectivity. About 51% of the road network and 54% of the surveyed roads, were classified as being at either 'negligible' or 'low' risk level. 'Moderate' risk characterised about 24% of the road network and 20% of the surveyed roads. About 25% of the road network and 26% of the surveyed roads were found to be at 'high' or 'extreme' risk.

7.5 Summary and Conclusions

For the purpose of this study, about 102 km of Stromlo Forest roads, represented by 254 and 431 drainage outlets from development and validation data sets, respectively, were examined. Analysis determined the statistically significant features, which predicted the risk of a hydrological connection between roads and streams, which comprised hydrologic distance between stream and road, hillslope gradient from road to stream, road contribution area (RCA), and the upslope contributing area (USCA). These results were developed as a logistic model (equation 7.1) using the development data set, which was then validated using the validation data set. The validation results suggest that the model successfully predicted more than 97% of the presence or absence of road-to-stream connectivity. Quantification of these factors for each drain, and comparison with threshold values, allows managers to determine the likelihood that discharge from any given road (drain) would result in discharge (and hence sediment) reaching the stream. This would identify the critical drainage points on each road for which maintenance (or re-design) was high priority. The results presented in this chapter show that using GIS techniques in combination with mathematical and hydrological models is very useful for determining the level of road-to-stream connectivity through estimating the distance between the outlets of drains and streams.

The results of this study show that 'threshold' values aimed at identifying road-to-stream connectivity can be calculated from hillslope gradient and contribution length or area, or hillslope gradient and distance between roads and streams. Connectivity between road drainage structures and streams, as well as rill and gully initiation and channel formation, can be identified using the threshold value approach and statistical analysis. This approach, while less accurate than the logistic model, is also very useful for interpretative purposes.

The results presented in this chapter show that threshold curves based on slope and contribution area can be used to predict the road-to-stream connectivity. Under any circumstances, the risk will be low when RCA is less than 40 m^2 and will be high when the RCA is more than 70 m^2, and when also taking into account the hillslope gradient. Therefore, the RCA and hillslope gradient can be used as two acceptable predictors for the likelihood of occurrence and the level of the risk in relation to gully initiation and/or channel formation at the outlets of the road drainage structures, and for road-to-stream connectivity. The results show that there was no road-to-stream connectivity for nearly 46% of the road drainage structures. About 54% of the road drainage structures were connected to a stream, including 27% gully connectivity, and 27% non-gully connectivity (21% diffuse connectivity and 7% stream crossings).

The risk of connectivity between forest roads and streams was mapped using the results of the connectivity analysis and a GIS-based application. All risk layers were mapped individually and then combined in a final risk map. Almost half (49%) of the Stromlo forest roads were classified as being at moderate or greater risk of runoff and sediment delivery to streams by road-to-stream connectivity.

The outcomes presented in this chapter will be used in the next chapter to develop an integrated forest road impact assessment and consolidated risk map for the forest road network. The processes developed for predicting the road-to-stream hydrologic distance and road-to-stream connectivity assessment described here will form the key element of FRIA method presented in Chapter 8.

Chapter 8
Conclusions and Implications

8.1 Introduction

Large areas of the world's forests, especially in developed countries, are managed for industrial forestry (FAO, 2005). Extensive unsealed forest roads have been built within them for wood transportation and forest management purposes. Unsealed forest roads are the main sources of sediment delivered to streams in these areas; past research has focused on determining the sources and quantity of this sediment, and on rehabilitation of the degraded areas. More recently, identifying the road segments which cause water quality deterioration due to road-derived runoff and sediment delivery has become a significant objective of forest road management. The research reported in this thesis is based on the hypothesis that, by analysing the attributes of an unsealed forest road and its surrounding terrain, it is possible to evaluate the risk that erosion from the surface of the road, or associated with the road drainage structures, will deposit water-borne sediment into an adjacent stream.

This research has developed a methodology, called *Forest Road Impact Assessment* (FRIA), to identify sections of roads which pose the greatest risk to the water quality of adjacent streams. FRIA is a GIS-based approach which uses a combination of techniques for analysing, assessing and modelling road impacts on sediment generation and delivery to streams. To develop the FRIA methodology, it was necessary to review currently available methods in the fields of GIS and risk assessment relevant to this problem, and to examine the feasibility of using certain terrain parameters as indicators for impact assessment and risk identification. This method also reduces the amount of fieldwork needed to make this assessment by using existing data sets and GIS techniques.

This final chapter comprises 3 main sections. The first section follows the structure of Table 4.1, and summarises the conclusions of each previous stage of the research, as described in Chapters 5, 6 and 7. The second section describes the FRIA - how the components of the method are combined to constitute a risk-based approach for assessing the impact of the forest road system on water quality - and presents a consolidated risk map and tables for the case study area. The third section considers the implications of the study for forest road management, and for research relevant to issues addressed by this thesis.

8.2 Summary of Conclusions of Each Stage of the Research

8.2.1 Experimental Approach, Design and Sampling Strategy

The case study research was conducted in Stromlo Forest, ACT, Australia, which was a convenient and appropriate location. The results of this case study demonstrate that the use of the road slope position as the basis for selecting field sampling locations allows compilation of a representative data set within the funding constraints such as those applying to the case study. These sample segments were employed to evaluate point and non-point sources and terrain based evidence of surface deterioration and sedimentation. The strategy used for sampling provided enough flexibility to gather data from road prism and associated road-to-stream hillslope area at the same time. The application for this approach has provided the data and information needed to analyse road and drainage structures, test the hypothesis of the thesis, and develop and validate the models predicting the probability of rill and gully occurrence on the road surface and at the outlets of the road drainage structures, and the probability of road-to-stream connectivity.

8.2.2 Terrain Modelling and Analysis

DTM is a new approach developed to derive and characterise the terrain parameters from DEM using GIS techniques. The analysis conducted in the case study research showed that using a combination of GIS techniques and mathematical processes is the most accurate – depending on the accuracy of the input layer (DEM) – and fastest way to calculate the terrain parameters needed for the risk assessment of forest roads. In this study, a DTM approach using relief analysis in the ArcGIS environment was used to derive and characterise the terrain parameters from the DEM raster layer of the study area. The primary terrain attributes – for example, slope, aspect, flow direction, flow accumulation, USCA and curvatures – and secondary terrain attributes – for example, CTI and SPI – were derived separately for the study. These layers were used in conjunction with the field data as independent variables in the analysis process. The effectiveness of the terrain parameters as predictive variables was evaluated using standard statistical tests.

8.2.3 Forest Road Analysis

The road analysis provided the basic information and data needed for selecting the road segments for sampling and further analysis. Management of the database is one of the most important parts of the FRIA method presented in this thesis. A comprehensive road and drainage database was developed as part of this study. This was done for both the data derived from terrain layers using GIS and data collected from the field using DGPS. The road class, road use, road geometry and road drainage structures were assessed and classified. These provided essential data and information needed for assessing and modelling risk.

8.2.4 Hydrological Analysis

Hydrologic analysis is an essential part of the methodology used in this study to test and evaluate the hypothesis. The DEM of the study area was used for watershed delineation in order to create basins and sub-watersheds, locate streams, and to parameterise the stream networks. The stream delineation process was necessary for the FRIA evaluation process, especially for the steps of flow distance calculation and assessing and modelling road-to-stream connectivity. Identifying and predicting the connectivity between roads and streams is probably the single most important component of the FRIA. Significant risks to the quality of the stream water occur when the runoff and sediment produced from the surface of the roads and outlets of the drainage structures are delivered to the streams. Consequently, three of the most important questions that were answered during the FRIA were: What is the probability of rill and gully erosion on the road surface or at the outlets of the drainage structures? How far are the roads located from the streams? Can the water flow reach from the outlet of road drainage structure to the stream? In this study, hydrologic distance between road and stream was predicted using different GIS-based models and was compared with the distance measured in the field. The comparative analysis demonstrated that the best hydrologic distance prediction models were 'GRIDPATH' and 'PTRA_LEN' resulting from the *FLOWPATH* and *FLOWLINES* models.

Road-to-stream connectivity was predicted using a threshold curve, logistic regression and GIS analysis to calculate the independent variables necessary to predict whether or not the runoff flow pathways originating from the outlet of drains would reach the streamline. The most accurately predicted distance, from *FLOWPATH*, was used in conjunction with field-collected data to assess the type of road-to-stream connectivity. This assessment showed which sections of the roads are most likely to deliver sediment associated with runoff to streams. The assessment also showed that using a two dimensional threshold curve of RCA and hillslope gradient provides a more accurate road-to-stream connectivity prediction than other methods.

8.2.5 Development of Rill & Gully Occurrence and Road-to-Stream Connectivity Risk Models

The relationship between rill and gully occurrence, and road-to-stream connectivity and independent variables was tested using a development data set comprising data collected from the field, terrain attributes derived from DEM by DTM, and those data calculated by hydrologic analysis. The sensitivity of independent variables was tested using a forward stepwise regression analysis. The logistic regression and other regression analyses were used to evaluate which variables were important in explaining rill and gully occurrence on the road surface and at the outlet of drainage structures, and road-to-stream connectivity.

After an extensive search of the literature, more than 35 variables (terrain attributes and data collected in the field) were selected for testing. The results of the analyses suggested that only a small number of variables were important in determining the risk arising from forest roads in terms of soil erosion and water quality. The reasons for this were:

1. Multi-collinearity among some variables. For example, there was a high degree of multi-collinearity found among RCW, RCL and RCA in the matrix of correlation of coefficients. Therefore, only RCA or RCL was used as a variable in the final analysis. There was also a high degree of multi-collinearity among slope, CTI, and SPI. Consequently, slope was used separately in the analysis in order to avoid any confounding effects on the estimation of the dependent variable;
2. Some independent variables were used to generate other variables and therefore they had an indirect effect when used to determine the elements at risk. For example, an analysis of slope stability was applied using the saturation zone for the area. To create this layer, DEM relief and topographic analyses were first applied. Some of the layers resulting from these - such as aspect, flow direction, flow accumulation and specific catchment area - were then used to create the saturation zone. Furthermore, elevation, flow direction, flow accumulation, and curvature are all necessary as input variables in delineation of the watershed and in stream network parameterization processes. Elevation was not a significant independent variable when used to predict the occurrence of rills and gullies on the surface of the

roads or at the outlets of the drainage structures. However, it is a most important primary terrain attribute for deriving other terrain attributes from a DEM. Moreover, land use, land classification, soil type, textures and characteristics and slope position were used to create other layers such as P, C and K Factors. They were also used for classifying the catchment area and roads in order to conduct the field survey and road-to-stream connectivity assessment. Type and density of vegetation and land management are very important variables affecting the value of the P and C or K factors, but they cannot be used directly in the models;

3. Some variables play a similar role in most of the road prism, and thus they were used only once in the analysis. Examples of these are climate (rainfall) and the vegetation cover on the cut and fill batters and on stream banks. Rainfall affects all of the road segments, particularly road surface or cut and fill batters, in the same way as a bare area. Therefore, this factor was used for predicting soil erosion from the catchment area and roads, but was not used for all sections separately as the average values of the infiltration and runoff rates for all segments are nearly identical. Because all vegetative cover on the study area was removed by the 2003 bushfire, strip buffers – among the most important variables affecting road-to-stream connectivity and sediment delivery – were not recognised as significant variables influencing the road-to-stream connectivity in the statistical analysis and developing model. The vegetative cover on the batters or on road shoulders were not also recognised as significant variables influencing rill and gully erosion on the road surface or at the outlets of road drainage structures in statistical analysis and model development;
4. Although some of the literature (see Chapters 2, 4 and 6) suggested that the height and slope of fillslope and cutslope, road use (traffic volume), and the age of the roads were significant variables influencing soil erosion of forest road systems, especially for the first few years after road construction, there was little evidence of the importance of these variables in this study. The data collected from the field showed that the average heights and associated slopes of cutslope were low (<1 m and <10%), and the road use was 'light', 'occasional' and 'no traffic'. Most of the roads selected for the study were stable because of their age and position on gentle and low slope terrain. Therefore, these factors were either not useful for the analysis or were not recognised as significant variables influencing erosion problems arising

from the roads. Road geometry was also not recognised as a significant variable influencing road surface erosion, but it was one the most significant characters of road surface used to identify the direction of the runoff flows on the road surface and record the RCW, RCL and RCA variables;

5. The result of the sensitivity analysis showed that presence or absence of some variables was not important to the final result. When their interrelationship and multi-collinearity were considered, they were removed. On the other hand, those variables which were retained could be justified by the results of the analysis.

Three logistic risk models were successfully developed for predicting the probability of rill and gully occurrence on the road surface and at the outlets of road drainage structures, and road-to-stream connectivity using the 'development' data set. The most important test was the goodness-of-fit test which was used to find whether the models fit to the data. An independent data set ('validation' data set) was then used to validate and test the accuracy of predictions from logistic regression models. The presence or absence of rill and gully erosion on the road surface and at the outlets of the road drainage structures and road-to-stream connectivity was estimated using the logistic models and found to match the observed condition (validation data set) on more than 96% of occasions. The usefulness of these models and how they can aid forest road managers will be discussed in section 8.3. Slope, road contributing length and area, CTI, road-to-stream hydrologic distance, USCA and hillslope gradient were commonly found to be important independent variables influencing rill and gully occurrence on the road surface and at the outlets of the road drainage structures, and in road-to-stream connectivity.

8.2.6 Risk Assessment and Mapping

A set of risk assessment procedures and risk criteria for assessing risk arising from forest roads impacting on soil and stream water quality were developed to compile the relative risk maps. The risk map of each component was created using the procedures and criteria presented in Chapters 2 and 4. As the pixel approach and grid layer were used to draw risk maps, the risk ranking scores were first estimated for each component and the score associated with each cell in the risk was then used to evaluate the level of risk, from extreme to negligible. Four risk components – soil loss, rill and gully erosion on the road surface and at the outlets of road drainage structures, and road-to-stream connectivity – were successfully mapped.

8.3 Integrating the Results of the Study into a Risk-Based Approach for Assessing the Impact of the Forest Road System on Water Quality

Making a decision generally includes consideration of three main areas: benefits, risks and costs. The economic aspect of the decision is related mostly to assessment of the benefits and costs, and is not directly discussed or included in this model. The method presented in this thesis only deals with the risk elements, and answers the question: 'How can we assess the risk that forest roads will deliver water-borne sediment to an adjacent stream?' When the risk is assessed for each drainage point in turn along an unsealed forest road network, the risk scores can be combined through integrating GIS data layers and creating a composite map. In this approach, the Multi-Criteria Evaluation (MCE) and overlay applications modules available in ArcGIS and IDRISI are the most important methods used to integrate GIS data layers in order to create a composite raster map.

8.3.1 Integrating the Components: Forest Road Impact Assessment (FRIA)

The Forest Road Impact Assessment (FRIA) method developed in this thesis is based on a practical approach that has the advantage of integrating existing knowledge into a logical framework of rules and relationships and provides a mechanism for evaluating the relationships. The aim is to formalise and simplify the risk assessment within a structure that is helpful for decision-makers.

Figure 8.1 illustrates the FRIA method as a flow chart model. All processes and procedures involved in the risk evaluation for the forest roads presented in the thesis are summarised in this figure. The forest road layer represented in Figure 8.1 is an input layer incorporating data describing slope position, road use and road age analyses, road prism characteristics, road surface condition and maintenance, cut and fill batters' characteristics, and road and stream parameterisation, all of which are necessary for developing a road database for use in FRIA.

The methodology illustrated in Figure 8.1 supports the concepts and procedures of assessing and then managing the risks arising from forest roads. As can be seen from the figure, the method comprises the following steps:

1. Map preparation;
2. GIS, DTM and Topographic Analysis in order to create and parameterise the terrain layers;
3. Sampling and field data collection;
4. Data preparation;
5. Applying RUSLE using GIS;
6. Hydrologic analysis, watershed and stream delineation;
7. Predicting the road-to-stream hydrologic distance using GIS-based modelling;
8. Road-to-stream connectivity analysis and modelling;
9. Statistical analysis and model development;
10. Creating individual and integrated risk maps for risk components;
11. Combining the risk layers using MCE or overlay application in order to draw the final consolidated risk map.

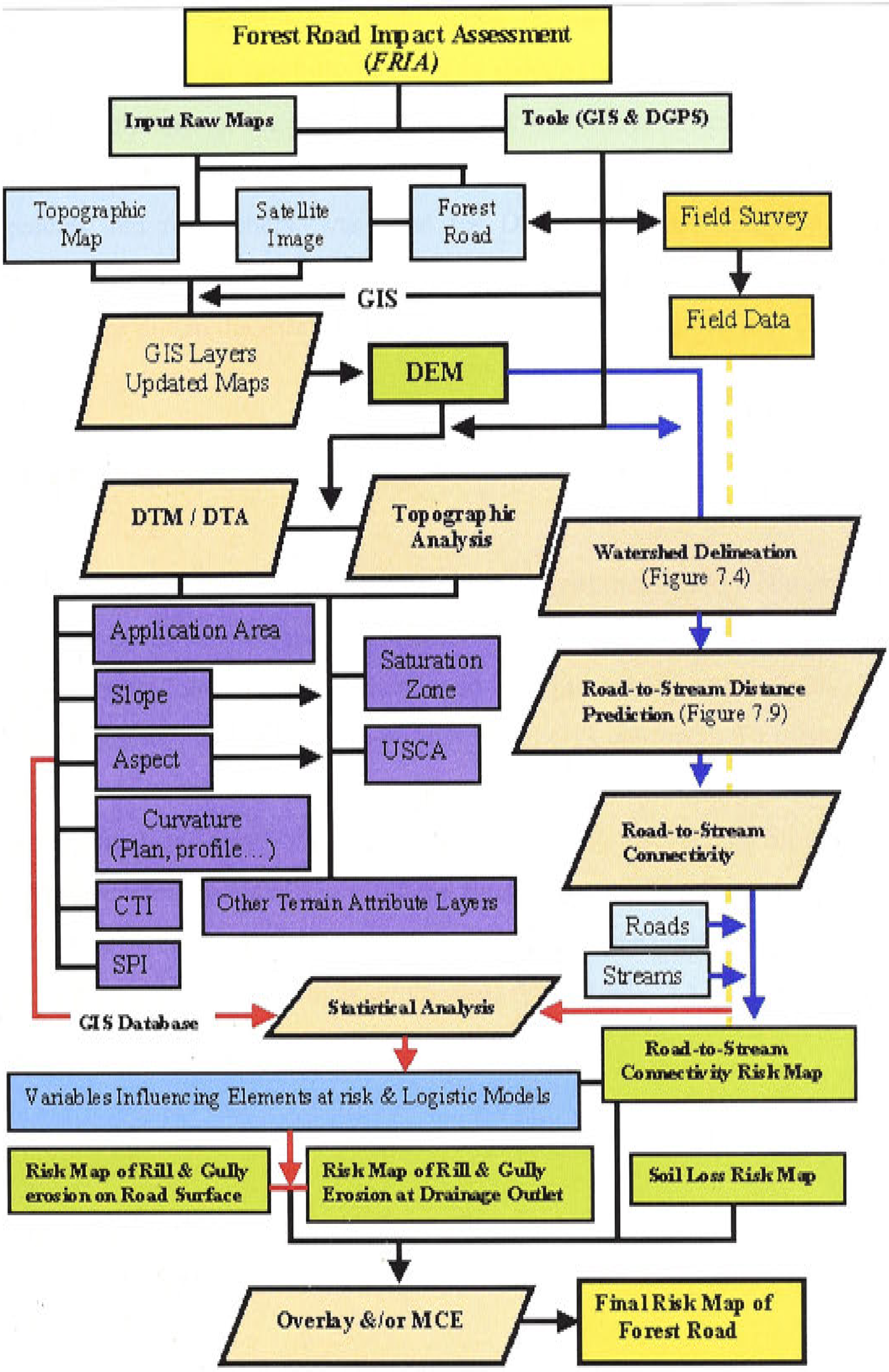


Figure 8.1. Forest Road Impact Assessment (FRIA): a GIS-based method for mapping the risks arising from forest roads on water quality

Most of the steps described above can be carried out using GIS techniques, and GIS was the main tool used in developing this method. As almost all GIS applications of the method are related to the layers derived by Digital Elevation Model (DEM); the accuracy of the

DEM also plays an important role in the outcomes and final results. The DEM must therefore be built up carefully in order to reduce the uncertainty of the layers derived and the final outcomes of the GIS modelling. For this study, as described previously, a DEM of 20 metres resolution (CRES, 2003), which is widely used by NSW and ACT Government agencies and researchers, was used for DTM and other GIS applications. Watershed delineation and road-to-stream distance and connectivity modelling are also critical applications due to the extensive use of algorithms, calculation, and GIS application.

8.3.2 Consolidated Risk Map

The final consolidated risk map is a combination of the different components – soil loss, rill and gully occurrence on the road surface and at the outlets of road drainage structures, and road-to-stream connectivity – developed and presented in this thesis. The risk from all components was calculated using a cell-based GIS approach. To create the final risk map, scores were assigned for each component, as described in Chapters 4, 6 and 7. The components listed above were aggregated by adding their scores for each area in each pixel to produce an aggregated score for the final risk map. The final risk map is presented as a set of grid layers using GIS overlay applications representing risk. It is a ranked risk map, and accompanies a table which summarises the results.

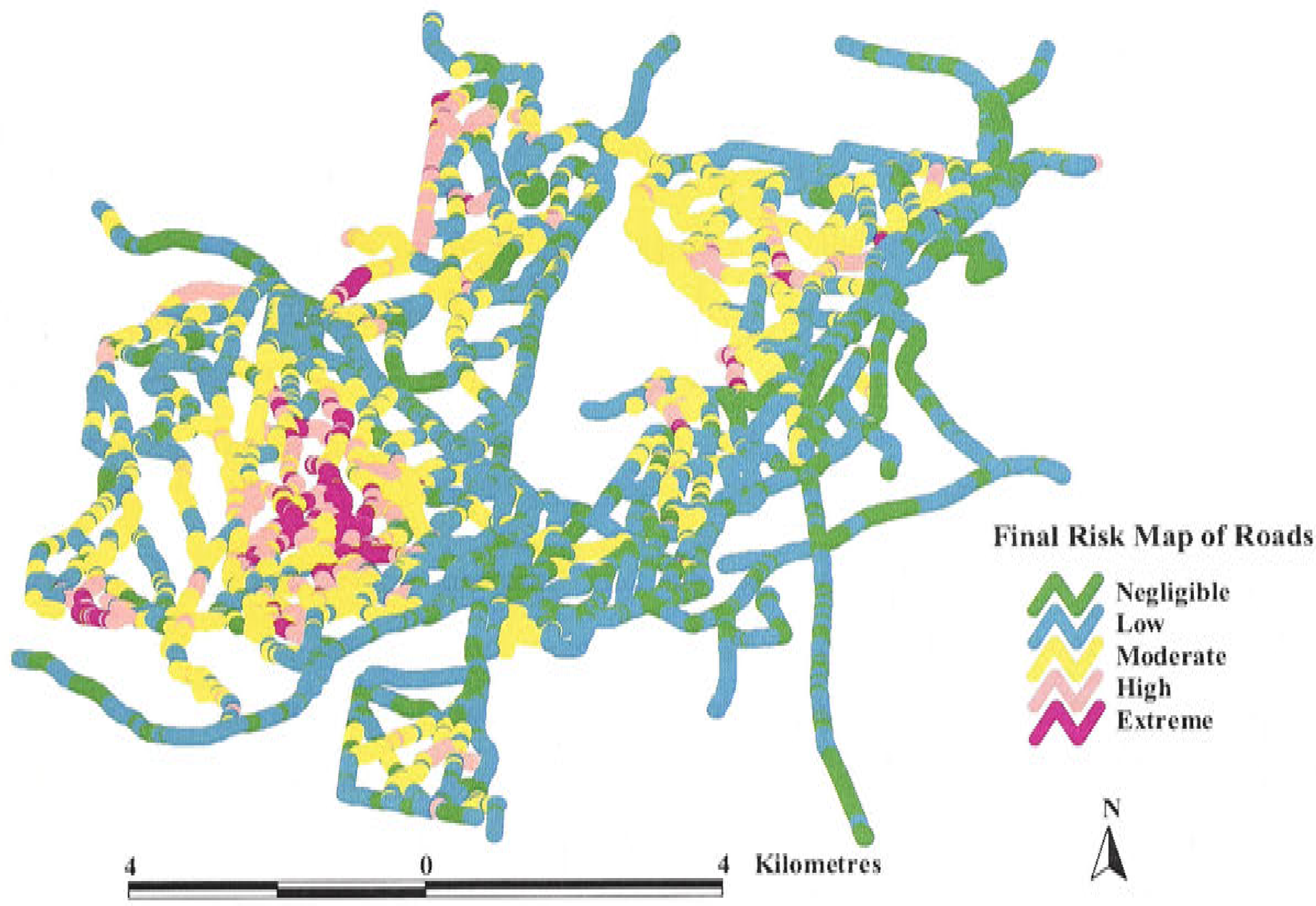


Figure 8.2. Consolidated risk map for the Stromlo Forest road network

The risk map for all forest roads in the study area, presented in Figure 8.2, is the final product of the FRIA developed in this thesis. Thus the final consolidated risk map of the forest roads is a combination of all components including road-to-stream connectivity risk layer and variables evaluated during this study. The areas of highest risk (road segments) are highlighted and can be easily identified for management purposes. These will need to be observed, investigated, supervised and maintained more closely than other areas.

Table 8.1. Summary of the final risk evaluation for the Stromlo Forest road network

Risk classes	Field survey roads		All roads	
	km	%	km	%
Negligible	16	16	55	18
Low	45	44	122	40
Moderate	26	25	67	22
High	11	11	28	9
Extreme	4	4	12	11
Total	102	100	307	100

Table 8.1 summarises the results of mapping the risk of the Stromlo Forest road network. The classification for whole study area (all roads, 307 km) was estimated from the sample segments (field survey roads, 102 km) following the procedures described in Chapters 6 and 7. The table shows that more than 58% (172 km) of the whole road network is predicted to have no significant adverse effects on the elements at risk, as they are classified as having 'negligible' or 'low' risk. About 22% (67 km) of the whole road network is predicted to have 'moderate' risk. About 20% (63 km) of the road network is classified as having 'high' or 'extreme' risk.

The roads classified as having 'extreme' risk are very sensitive and have a high potential to cause serious impacts on soil and water. A regular maintenance program alone cannot control the risks arising from these roads. Neither can the risks be significantly reduced by a very detailed maintenance program where the roads are located very close to streams (Furniss, *et al.*, 1997; Flanagan *et al.*, 2003).

The management and mitigation of risks arising from forest roads generally involve more than estimating the level of risks associated with the forest roads. As demonstrated in Chapters 5, 6 and 7, the risks of different components associated with the road segments are not equal; the risk of rill and gully erosion on road surface and at the drainage structures associated with the road segments located on steep terrain is quite different from the risk associated with those road segments located on flat areas. The risk of whether the material from erosion will reach a stream mostly depends on the location of the roads, the hydrologic distance between roads and streams, and the parameters producing energy essential for water movement (rainfall, the contributing area, and hillslope gradient). As described in section 8.4.5, forest and road managers should focus on the variables over which they can exercise control in order to minimise the environmental problems associated with the roads. The risk map approach can also assist forest road managers to make better decisions about the way they will reduce the risks associated with the forest roads.

8.4 Implications of the Study for Forest Road Management and Research

8.4.1 Experimental Approach, Design and Sampling Strategy

The research work conducted for this study demonstrated that the experimental approach and sampling strategy developed for collecting data from the field is appropriate for assembling and updating data and information essential for road management (for example, maintaining road drainage structures). The road inventory forms developed for collecting data would facilitate efficient assessment of a road and its drainage structures for maintenance purposes.

This experimental design approach, based on those developed and applied by many researchers cited in this thesis, proved an acceptable approach for sampling road segments. This procedure is particularly useful for surveying roads for which there is no information about the population parameters that are essential for estimating sample size. The sampling strategy and the procedures developed for collecting data in this study can be used as a model for data collection in similar research.

8.4.2 Terrain Modelling and Analysis

GIS is a common tool used for forest management in most forestry organizations. A DTM, therefore, can easily be used to provide essential terrain data from a DEM needed for forest road management. The procedures developed in this study to use terrain parameters for forest road risk assessment can be used as a basis to systematise forest road management. Using this approach will reduce the time and cost needed for collecting data from the field. For example, estimating hillslope gradient at the outlets of road drainage structures is time-consuming, and is difficult to measure accurately where the forest density is very high.

Calculating this slope using DTM from an accurate DEM would provide the slope layer with acceptable accuracy; however, this is not recommended when the DEM error is high.

Terrain analysis and DTM have well been documented, developed and used as GIS-based methods by many researchers in the last two decades. This study has further developed the use of DTM and terrain attributes to assess the risk for water quality associated with forest road segments. This process can be used as a powerful tool in similar research.

8.4.3 Forest Road Analysis

The procedures used here for forest road analysis can be used by forest road managers to gather the data needed for good road management. The time needed for field data collection can be reduced if a database of road layout and drainage structures exists. Because the information that exists in maps can become outdated quickly, conducting similar analysis and updating the database on an ongoing basis would greatly facilitate management to address the adverse impacts of forest roads on water quality. In addition, slope position analysis would be a useful form of terrain analysis for forest road management, to assess the location of the roads compared with the location of the streams.

Many researchers have used road analysis, especially road slope position and road use analysis, for detailed field surveys and assessment of forest roads. As in many of those studies, the procedures used in this study for road analysis demonstrate how it can be used effectively as the basis of improved forest road management.

8.4.4 Hydrological Analysis

The processes used in this study for predicting road-to-stream hydrologic distance and assessing road-to-stream connectivity are practical approaches that can be used to assist in forest road management. The prediction of the hydrologic distance between roads and streams is a very important step in the design, construction and maintenance of forest roads.

It is impossible to manage the water quality impacts of forest roads without knowing where the road-derived runoff concentrates, how long it flows, and whether it reaches a stream. Measuring road-to-stream hydrologic distance is time-consuming and expensive, comprising about 50% of the time spent collecting data for each drain. In addition, modelling the distance prediction between roads and streams requires extensive work and field data collection at drainage points.

The method for road-to-stream distance prediction introduced in this research uses GIS techniques to create the necessary points on the road layer, at different densities based on the approximate drain spacing. This approach allows data needed for analysis to be produced using topographic analysis, drain (point) parameterisation, and data derivation from the terrain layers. The terrain layer is used as point input to calculate the distance to streams and the slope gradient for the analysis is derived from a DEM. RCL can be estimated by the approximate drain spacing and, as most of road surface shape or road geometry is crowned, RCW can be estimated by using half the road width; thus, RCA is derived simply. The results of this method are very useful for managing forest roads to maintain water quality. When incorporated into a decision support system, forest road managers can use this method to routinely design a new forest road, or maintain an existing road.

As reducing the time, and therefore cost, of fieldwork is one of the main aims of this study, predicting the hydrologic distance by modelling and use of GIS-based applications with an acceptable accuracy are fundamental to the approach. The results of the connectivity assessments provide information to help forest road planners and managers mitigate the risk of the road-derived runoff and sediment to streams. However, it should be noted that all results presented in this thesis are related to field evidence as observed in the case study site in 2003/2004; the model may not cover a heavy rainfall or storm event, such as those likely to occur at a $\geq$50-year recurrence interval.

Several approaches to assessing the hydrologic impacts of forest roads were successfully tested in this study. The combination of GIS techniques and the models developed for road-to-stream connectivity (for example, Vbt5 and threshold curve) can be used to assess the likelihood of delivery of sediment to streams from forest roads. The results of this study demonstrated the usefulness of using these models for predicting road-to-stream connectivity, and suggest that the procedures used in this study would be useful in similar research or research applications.

Reducing Fieldwork by Modelling Hydrological Distance and Connectivity

The development of an automated road-to-stream distance calculation using GIS-based model application has been described in Chapter 7. The results of this automated distance calculation are very useful for reducing the amount of fieldwork and therefore reducing the cost of evaluations. The best use for this method is the evaluation of a mapped or designed road alignment, before drains are installed. The results presented in Chapter 7 have also identified a method of calculating the distance between roads and streams with much higher accuracy when compared with the field measured distance than other applications.

A related outcome of the work is that it informs how fieldwork for Forest Road Impact Assessment (FRIA) might be conducted more efficiently. Forest road impact assessment needs extensive fieldwork. One of the main objectives of this study, described in Chapter 1, was to find a method using GIS that would reduce the amount of fieldwork. As field measurement of the distance between roads and streams is time-consuming and expensive, GIS techniques were used to automate the calculation of the distance. Field data collection to record road drainage structures in order to assess impacts of road on soil and water quality is also time-consuming and expensive. A GIS-based method, described in Figure 8.3, can be used to find the potential locations of the drains, predict the hydrologic distance, assess the road-to-stream connectivity and map the risk arising from this connectivity. The road layout of the study area was used as an input layer and points on this network were randomly generated using ArcGIS commands and ArcView. The aim was to generate points on the roads where drains would most likely be installed. Therefore, the average distance between the sampled drainage structures, the nodes of the roads, any changes of direction and distances between the points were the main factors that were considered in point generation. The points were generated at different distance thresholds in order to cover all road sections.

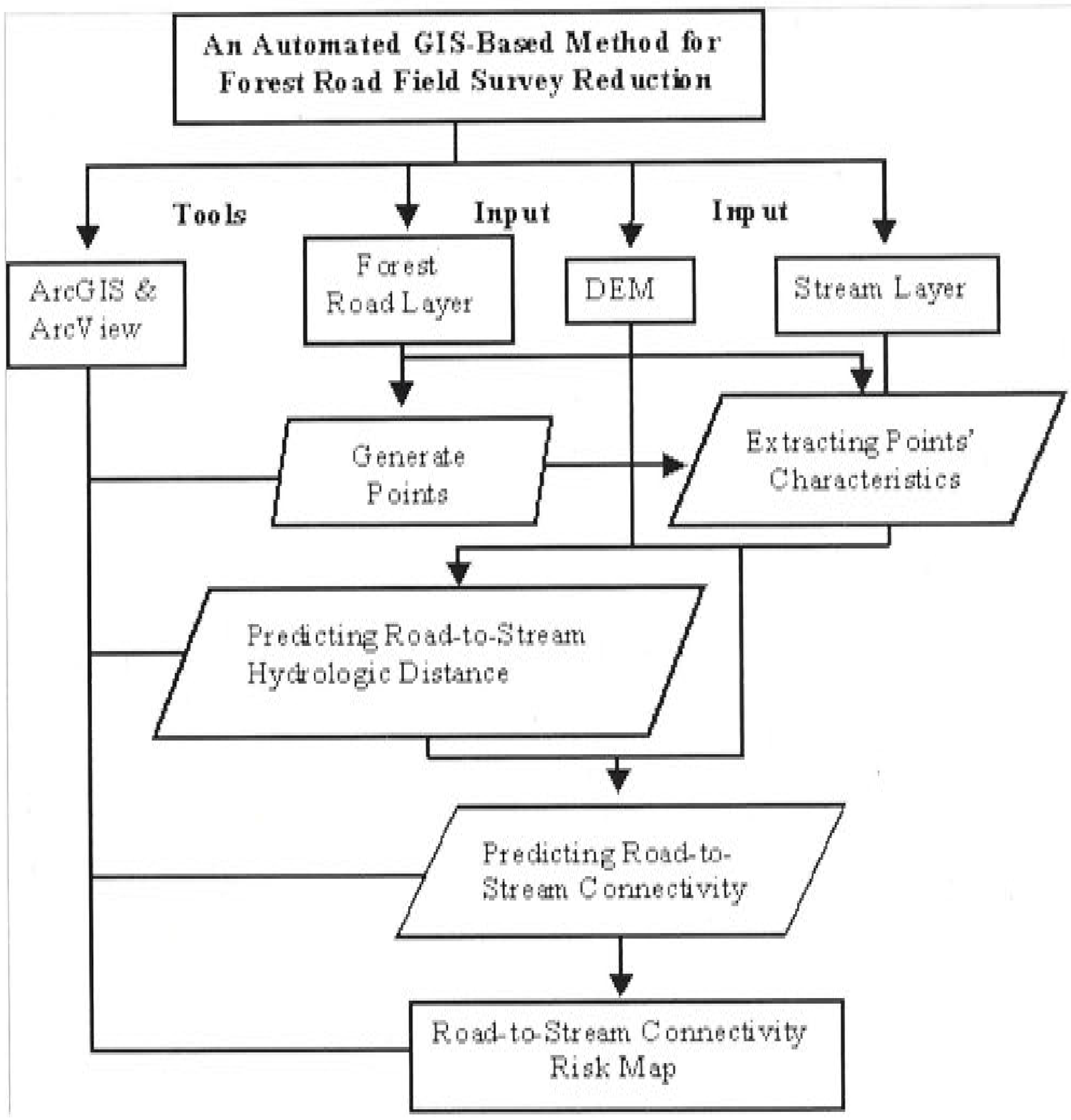


Figure 8.3. GIS-based method used to draw the risk map of road-to-stream connectivity aiming to reduce field sampling

The points were generated and stored as shapefiles and then converted to coverage layers for using as input layers in the model application. The DEM and road layers of the study area were then used for extracting the point characteristics such as elevation, position (X and Y), and the road types and characteristics where the points were located. The point generated layer was used to predict the hydrologic distance between roads and streams using the GIS-based models described in section 7.3.2. As the generated points were randomly distributed throughout the road network, the distance can be predicted for the entire road network. It is therefore possible to assess the road-to-stream connectivity for the entire forest road network.

This method can be used in both planning and designing a new road and maintenance processes for an existing road. The advantage of this automated system is to handle a case where a new roading system has been designed as far as the road alignment and provides an automatic method for assessing where the drains should be placed. This would save a lot of fieldwork and raise the level of environmental protection needed for the road drainage. For forest road planning, the road layout designed for construction can be automatically assessed in order to find the likelihood that road and stream will be linked. This can also be used for installing drainage structures in the best positions on the road, according to the distances between roads and streams and their connectivity. It can also be used to evaluate an alignment before drainage features have been installed.

The road designers and managers can use this map as an important tool to find which road segment is at risk. The drainage structures and roads, therefore, can be aligned by (1) locating in the best position along the roads, (2) selecting an accurate drain spacing to avoid environmental problems, (3) designing the road surface (geometry) in order to redirect the runoff in the right direction to avoid road-to-stream connectivity, (4) re-alignment of the road layout if other options do not work.

Existing roads can also be assessed for maintenance purposes using this method. For example, in a situation similar to that of Stromlo Forest, where most mitre drains are installed by a grader and the road surface is graded once or twice a year (major and minor access roads), the mitre drains and the road geometry can easily be managed by using the road-to-stream risk map to avoid environmental problems.

Slope gradients measured in the field were compared with the slope gradients, which were derived from the DEM using GIS. The comparison showed a strong relationship (correlation coefficient $r = 91$, $r^2 = 0.83$ and $P < 0.0001$) between hillslopes measured in the field and hillslopes derived from the DEM. As measuring the slope gradient in the field (using clinometer to $\pm$ 0.5°) is time-consuming and therefore expensive, using a derived slope gradient will reduce the amount of fieldwork dramatically.

8.4.5 Development of Rill & Gully Occurrence and Road-to-Stream Connectivity Risk Models

As described previously, three logistic models were developed to predict rill and gully occurrence on the road surface and at the outlet of the road drainage structures, and the probability of the road-to-stream connectivity. The models can be used to assist forest road management by informing managers about the consequences of varying the parameters over which they have some control, and which are recognised by the models as influencing erosion processes or road-to-stream connectivity.

Not only does rill and gully formation on a forest road surface indicate the possibility of sediment discharge, it also indicates a deterioration in the road surface that will affect its trafficability. The equations that predict the occurrence of rills and gullies can also be used to determine how modifying the parameters can improve the situation. This is illustrated in Table 8.2. For example, where gullies and rills are predicted as certain to occur ($p>70\%$), reducing Road Contributing Area (RCA) to less than 37 m^2 or realigning the road to slope less than 5%, would change the likelihood of occurrence of erosion to 'virtually certain not to occur'. This example illustrates the simplest situation in which only one variable is altered. In practice, it is likely that all three variables would be altered. The predictive equation allows the manager to assess how much adjustment is necessary to achieve the desired result. For example, RCA is a manageable variable, and can be altered by reducing drain spacing to control or minimise surface erosion. For road sediment to reach a stream, it is necessary both that erosion occurs on the road surface or at the outlets of the road drainage structures, and that there be a road-to-stream connection. The models allow the manager to assess whether reducing one or more of the road surface erosion, drainage outlet erosion, or road-to-stream connectivity is the most effective course of action.

To illustrate this potential, the median value of each variable was calculated using nonparametric tests (K Independent Samples provided in SPSS software) based on the dependent variable. For each case, this median value of all significant variables was entered as constant. The value of each variable was then altered separately, and the probability of erosion predicted. For example, using the equation for predicting the probability of rill and gully occurrence on the road surface (equation 6.1), the values of RCA, slope and CTI were altered separately while holding others constant at their median value. Using this process, the values needed to give predicted probability values of ≤30, >30 - ≤50, >50 - ≤70, and >70, were determined. Results are summarised in Table 8.2.

Table 8.2. The predicted probability of rill and gully occurrence on the road surface, and associated altered values of RCA, slope and CTI, with the value of other variables held constant at their median

Altered value of RCA (m^2)	Altered value of slope (%)	Altered value of CTI (Index)	Predicted Probability (%)
≤37	≤5	<3	≤30
>37 - ≤44	>5 - ≤6	>3 - ≤5	>30 - ≤50
>44 - ≤51.3	>6 - ≤8	>5 - ≤7	>50 - ≤70
>51.3	>8	>7	>70

Similarly, Table 8.3 shows the effects of using the model represented by equation 6.2 to predict rill and gully erosion at the outlets of road drainage structures, by altering the value of each of the variables RCA, slope and CTI separately while holding other variables constant at their median value. In this case, where gullies and rills are predicted as certain to occur (p>70%) at the road drainage structures, reducing RCA to less than 25 m^2 or installing the road drainage structures where the hillslope gradient is low (<8%), would alter the likelihood of occurrence of that erosion to 'virtually certain not to occur'.

Table 8.3. The predicted probability of rill and gully occurrence at the outlets of road drainage structures, and associated altered values of RCA, slope and CTI, with the value of other variables held constant at their median

Altered value of RCA (m^2)	Altered value of hillslope (%)	Altered value of USCA (m^2)	Predicted Probability (%)
≤25	≤8	<80	≤30
>25 - ≤40	> 8 - ≤12	>80 - ≤150	>30 - ≤50
>40 - ≤55	>12 - ≤15	>150 - ≤222	>50 - ≤70
>55	>15	>222	>70

Table 8.4 shows the effects of using the model represented by equation 7.1 to predict the probability of road-to-stream connectivity by altering the value of each of RCA, slope, USCA and distance to stream when holding the others constant at their median value. For example, where road-to-stream connectivity is predicted as certain to occur (p>70%), installing road drainage structures where the hillslope gradient is less than 14%, or changing the alignment so that road-to-stream hydrologic distance is more than 300 m, or

reducing the road drain spacing, would mean that connectivity - especially gully connectivity - was virtually certain not to occur. The values of independent variables that shift the probability to the key values are shown in Table 8.4.

Table 8.4. The predicted probability of road-to-stream connectivity, and associated altered values of RCA, slope and CTI, with the value of other variables held constant at their median

Altered value of RCA (m^2)	Altered value of hillslope (%)	Altered value of USCA (m^2)	Altered value of distance (m)	Predicted Probability (%)
<33	<14	<100	>300	≤30
33 - ≤49	14 - ≤16	>100 - ≤186	<300 - >200	>30 - ≤50
>49 - ≤65	>16 - ≤18	>186 - ≤270	<200 - >87	>50 - ≤70
>65	>18	>270	<87	>70

Information obtained from the use of these models, such as that above, can be used to manage existing roads better. For example, in a situation similar to that of Stromlo Forest, where most mitre drains are installed by a grader and the surface of major and minor access roads is graded once or twice a year, spacing of mitre drains and the road geometry can easily be managed according to the altered values to maximise the likelihood of avoiding rill and gully erosion on the road surface and/ or at the outlets of road drainage structures or road-to-stream connectivity. By changing the positions of the drains, especially mitre drains, the effects of hillslope gradient and distance between roads and streams on the elements at risk can be controlled. The drains of those outlets that are more likely to be connected to streams can be managed by a maintenance program using the risk map as the basic tool. For example, the drainage structures that are installed where the hillslope gradient is high, or road-to-stream hydrologic distance is short, may require sealing and re-diversion of water flow because of the road-to-stream gully connectivity.

Road designers and managers can also use this information when planning and designing a new road, by designing road segments that are within safe limits of the manageable variables. The roads, therefore, can be aligned within slope limits, drainage structures located in the best position along the roads (for example, where the hillslope gradients are lower), an accurate drain spacing selected, and the road located far enough away from the stream to avoid connectivity to streams. This information can be used in conjunction with the forest road risk map which will identify the critical road segments. Results of this study also suggest that the site conditions and location of the drainage structures are more important than maintenance practices in determining the erosion and water quality impacts arising from the unsealed forest roads.

Regression analysis, especially logistic regression models such as those used here, are generally used by researchers to evaluate which variables (for example, site factors) are important in explaining erosion occurrence or to predict presence and absence of erosion on the road segments (for example, Croke and Mockler, 2001; Madej 2001; Megahan *et al.* 2001). This study successfully used logistic regression to evaluate selected road segments in terms of presence or absence of erosion or road-to-stream connectivity.

8.4.6 The Benefits of Risk Assessment and Mapping and Implementing the FRIA Method

The process of risk assessment and mapping described in this thesis can assist forest road managers to make better decisions about how they will reduce erosion and sedimentation risks associated with the forest roads. The level of risk associated with each road segment can easily be identified using the consolidated risk map, providing managers with a clear and objective basis for decision-making.

A formal risk assessment framework and methodology, such as that described in this work, has been widely applied to various forestry activities by many researchers in recent years. This study has demonstrated how the risk assessment process, and its visualisation as a map, can be applied to assess and manage the risk associated with forest roads impacting on soil erosion and water quality. The risk assessment procedures developed in this study can be used, in conjunction with those published in the literature, to further develop risk assessment and management processes in other aspects of forestry and natural resource management.

The FRIA method developed in this research provides a systematic approach to minimise and manage the impacts of the roads on water quality, by managing the most important variables influencing those impacts. One of the advantages of the method is that it incorporates as many, or as few, of the individual assessments on which it is based as necessary, or as are available. This means it is quite flexible in its implementation. Because the final outcomes of this method are easily understood as a colour-coded risk map and/or summary table of results, the outputs are readily used by non-expert forest managers. Similarly, a competent GIS analyst can carry out most applications of this method using standard GIS techniques. For example, applying RUSLE can be a complicated task for someone not expert in that methodology; however, if drawing a coherent picture of the distribution of potential soil erosion from a forest road is of interest, an erosion index map can be simply drawn, using topographic and DTM analysis and the mapped outcomes of the sediment transport index equation. All related processes such as derivation of slope, specific catchment area, CTI, SPI, and calculation of the slope length factor can be accomplished using the widely-available ArcGIS software.

The major benefits of the FRIA method developed here are summarised below:

1. It is a practical method, and the outcomes of applying it can be used directly in both designing the road layout and maintenance of the existing roads;
2. The effects of different variables on the elements at risk can be visualised (as a GIS risk layer) and tabulated (for example, as a GIS database). Therefore, there is flexibility to apply very detailed GIS and statistical analysis for specific purposes;
3. Impact assessment of forest roads is generally time-consuming and expensive because extensive fieldwork is needed for the evaluation process. One of the main aims of the study was to devise a method that would reduce the amount of field survey work needed. The method achieves this goal by using spatially-explicit modelling, and the case study research has demonstrated the accuracy of the slope and hillslope gradients, the most important variables for impact assessment, derived from a DEM compared with those measured in the field.
4. The road-to-stream connectivity analysis presented in Chapter 7 can be used to plan the design, construction and management of a forest road network. All the steps necessary for evaluating the risk roads pose to stream water quality can be applied using GIS techniques and applications, without gathering data from the field;
5. The consolidated risk map of the forest roads integrates the prediction of two main risks identified in the objectives of the study – the probability of erosion associated with road surfaces and drainage structures, and the probability of stream water

deterioration from the sediment produced by this erosion – by predicting the degree and type of the road-to-stream connectivity. Erosion of the road surface itself may not represent a risk to water quality, unless the sediment produced reaches an adjacent stream. The consolidated risk map shows areas where there is both erosion and connectivity, which is of critical interest and importance to managers.

Of course, the implementation of the method proposed here has costs, which forest owner and manager must judge against other expenditures, and the incomes and/or cost saving associated with them. It would be also helpful for the costs and benefits associated with implementation of FRIA method to be considered in the context of a forest estate resource allocation (that is economic) model.

8.5 Recommendations for Future Work

While the framework of the FRIA method developed here is quite robust, its specific components would benefit from being tested in other regions with characteristics different from those of Stromlo Forest. This research would include testing the utility of the models found to be most appropriate in this study. Examples of other relevant GIS-based models are SEDMODL2 (NCASI, 2002) and WEPP (Flanagan and Livingston, 1995); these have used principally the technical specifications of forest roads to predict either soil erosion or potential sediment delivery to streams under the specific defined conditions in North American forests, and could be adapted to Australian (and other) conditions. It could also be helpful to explore other approaches to integrating GIS layers: in this study, the integration of risk layers has been carried out using either Multi-Criteria Evaluation or overlay application provided in ArcGIS and IDRISI. Use of these tools requires lengthy and painstaking work, and it would be informative to test the efficacy of other possible methods for combining GIS layers.

Some variables known from the literature to have an important influence on sheet erosion from the road surface were found to be non-significant when the logistic models were developed for this study. Examples of such variables are road use, time since construction, maintenance frequency, cutslope gradient and vegetation coverage on the cut and road shoulders. The probable reason for this was that these variables showed little variation in the mature road network of the case study area. For example, no road selected for sampling in the study was subject to greater than 'light' use, and all cut and fill batters were stable because of the period elapsed since their construction. It is therefore recommended that the FRIA method be tested on forest road networks where these variables exhibit a greater range of values. For example, the K-factor used in the RUSLE would have to be recalculated for the case of heavy use intensities on unsealed forest road.

As the applicability of the method is verified and further enhanced, it would be very helpful for potential users to develop the software as a toolbox, to be used in conjunction with appropriate GIS software (for example, ArcGIS and ArcView). There are examples of such toolboxes for other forestry applications – for example, Private Forestry Tasmania's 'Farm Forestry Toolbox' (PFT, 2004), for assisting management of private planted forests, and the Dry Sclerophyll Forest (DSF) and Woodlands Management Toolbox being developed in the School of Resources, Environment and Society (SRES), ANU (B.J. Turner, pers. comm., 12 May 2005). Common computer languages such as Visual Basic are very useful in creating such a toolbox with GIS specifications. The main advantage of developing and presenting the methodology as a 'toolbox' is to automate many of the FRIA processes and procedures in a decision support system, and enhance ease of use and consequently uptake by forest managers.

Finally, this study has demonstrated the importance of an accurate DEM with good resolution. The preliminary analysis and DTM were applied using a DEM at 40 m resolution, but the results were not sufficiently accurate to be useful. Consequently, use of an accurate DEM, at 20 m or finer resolution, is necessary for application of the FRIA method described here. The acquisition and verification of such DEMs might be a priority for forest managers.

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Appendix A. Field Survey Forms Used for Collecting Data from the Field

1. Field survey form for collecting data from forest road drainage structures

a. Drains

Road name: Road segment's No: Area name/s: Equipment:

Date: Time:

Section 1. General information
1.1 Drain N: 1.2 Types of Drain: a. Mitre b. Cross–Bank
C. Push-out 1.3 RCW: m 1.4 RCL m
1.5 Slope @ inlet %/degree 1.6 Slope @ outlet %/degree
1.7 Slope @ channel bed %/degree 1.8 Direction (angle) degree
1.9 Width m 1.10 Length m
1.11 Depth m 1.12 Location: a. left b. right

Section 2: Design construction
Drain classification
a: 1 b: 2 c: 3 d: 4 e: 5 f. 6

Section 3. Erosion and water pathway
3.1 Evidence of erosion on the surface of the roads:

3.2 Sedimentation in the table drain and at the outlet:

3.3 Is drain selected for measuring distance road–to–stream? a. Yes b. No
3.5 Distance between mitre drain and stream m
3.6 Flow pathway length m
3.7 Has flow reached the stream? a. Yes b. No Gully/diffuse

Section 4. Drains' characteristics
4.1 Characteristics of drain and condition at the inlet and outlet:
4.2 Characteristics of cross–banks:
4.3 Characteristics of push–outs:

b. Culverts

Road name: Road segment's No: Area name/s: Equipment:

Data: Time:

Section 1. General information 1.1 Culvert N: 1.2 Types of culvert: a. Relief b. Stream crossing 1.3 RCW: m 1.4 RCL m 1.5 Size cm/m 1.6 Slope at the inlet %/degree 1.7 Slope at the outlet: %/degree 1.7 Direction (angle): degree 1.8 Location: a. left b. right 1.9 Culvert working conditions a. Good b. Partly c. Blocked
Section 2. Design construction Construction at the inlet and outlet (classification): a: 1 b: 2 c: 3 d: 4
Section 3. Erosion 3.1 Evidence of erosion on the surface of the roads: 3.2 Sedimentation on the channel bed or at the outlet: 3.3 Channel formation 3.4 Is culvert selected for measuring distance road–to–stream? a. Yes b. No 3.5 Distance between culvert and stream m
4. Characteristics of culvert and condition at the inlet and outlet:

2. Special field survey form for collecting data from forest road prism

Road name: Road segment's No: Area name/s: Equipment:
Date: Time:

Section 1. Road surface 1.1 Road N: 1.2 Types of road 1.3 Road class: 1.4 Width m 1.5 Slope %/degree 1.6 Surface condition: a. Sealed b. Unsealed c. Ruts on the road 1.7 Types of soil and materials covering road surface: 1.8 Evidence of rill or gully erosion: 1.9 Traffic condition (vehicle pass): 2 Road's maintenance condition:
Section 2. Table drain (ditch) 2.1Is ditch installed along the roadside correctly? a. Yes b. No 2.2 Ditch's bed slope gradient % 2.2 Technical specifications: 2.3 Ditch working conditions: a. Good b. Not properly c. Partly D. Doesn't work 2.4 Evidence of erosion a. Table formation b. Table bed erosion c. Sedimentation 2.5 Ditch and drain interactions:
Section 3. Cut and fill batter Note: Do not record if there are no cut and fill batters of significant height 3.1 Height a. Cut m b. Fill (Width) m 3.2 Length a. Cut m b. Fill m 3.3 Slope a. Cut m b. Fill %/degree 3.4 Failure a. Cut Yes/No b. Fill Yes/No 3.5 Vegetation cover on the batters: a. Cut: a1. Under 25% a2. 25 – 50% a3. 50 – 75% a4. Above 75% a5. Other % b. Fill: b.1 Under 25% b.2 25 – 50% b.3 50 – 75% b.4 Above 75% b5. Other % 3.6 Evidence of erosion:
Note:

3. Special field survey form for collecting data from rill or gully erosion

Road name: Road segment's No: Area name/s: Equipment:

Date: Time:

Section 1. Road surface 1.1 Road N: 1.2 Types of erosion: a. Rill b. Gully 1.3 Width: cm/m 1.4 Depth cm/m 1.5 Length m 1.6 Slope %/degree 1.7 RCW 1.8 RCL 1.9 The origin of the erosion: a. Drain inlet b. Drain failure c. Ditch failure d. Ruts on the roads e. Others: 2 Technical specifications:
Section 2. Outlets of road drainage structures 2.1 Types of erosion a. Rill b. Gully c. Channel formation 2.2 Hillslope %/degree 2.3 Sediment plume (or sedimentation) a. Yes b. No 2.4 Waterway channel formation a. Yes b. No 2.5 Length of water pathway: 2.6 Drain and stream connection a. Yes b. No 2.7 Vegetation cover/strip buffer: 2.8 Road-to-stream hydrologic distance and connectivity: 2.9 Technical specifications:
Note:

Appendix B. Example of Field Data from Road Layout and Drainage Structures, Terrain Attributes and Predicted Road-to-Stream Hydrologic Distance

Appendix B Table 1. Example of field collected data and terrain attributes derived from DEM

ID	Feather Name	Field ID	Accuracy X	Accuracy Y	Accuracy Z	Channel Width (m)	Channel Length (m)	Channel Depth (m)
10	Drain	d1302	1.45	1.66	1.01	0.55	16.00	0.25
16	Culvert	c0402	0.1	0.19	0.14	-	6	-
16	Drain	d1308	2.20	3.06	1.06	0.22	11.00	0.18
17	Push out	d1309	1.18	1.44	0.82	0.54	12.00	0.21
22	Culvert	c0408	0.04	0.03	0.08	-	5.5	-
29	Drain	d1321	3.81	3.47	1.23	0.35	15.00	0.26
85	Culvert	c0371	0.05	0.22	0.15	-	6.5	-
33	C_Bank*	d1324	0.17	0.61	1.53	1.00	9.00	0.75
32	Drain	d1324	2.39	2.14	1.46	0.35	10.00	0.13
63	Culvert	c69703l	0.04	0.04	0.15	-	7	-
65	Culvert	c69705l	0.03	0.04	0.07	-	6	-
36	C_Bank	d1327	0.18	0.65	1.19	1.10	4.00	0.46
37	C_Bank	d1328	0.17	0.65	1.20	1.10	5.00	0.58
6	Drain	m7206	0.18	0.17	0.30	0.48	9.00	0.13
7	Drain	m7207	0.18	0.17	0.30	0.35	10.00	0.20
82	Culvert	c114502r	0.04	0.04	0.07	-	5.5	-
83	Culvert	c64701r	0.03	0.04	0.06	-	6.5	-
9	Drain	m7209	0.22	0.18	0.26	0.65	10.00	0.25
84	Culvert	c60301l	0.08	0.22	0.41	-	8	-
13	Culvert	c2401	0.06	0.07	0.13	-	6.5	-
11	Drain	m72011	0.22	0.18	0.19	0.68	18.00	0.26
48	Drain	m60501r	0.15	0.28	0.42	0.35	8.00	0.21
53	Drain	m59803r	0.15	0.23	0.39	0.38	13.00	0.20
54	Drain	m59804r	0.15	0.28	0.66	0.35	14.00	0.13
57	Drain	m59807r	0.14	0.23	0.25	0.28	12.00	0.13
59	Drain	m59809r	0.14	0.23	0.28	0.30	10.00	0.14
63	Drain	m59813l	0.14	0.22	0.26	0.28	21.00	0.20
66	Drain	m64402r	0.18	0.43	1.35	0.13	12.00	0.10
69	Drain	m62602l	0.05	0.15	0.57	0.57	17.00	0.25
71	Drain	m62604r	0.06	0.12	0.38	0.35	11.00	0.21
30	Drain	m64003r	1.42	1.34	1.43	0.2	13.00	0.15
32	Drain	m64005r	1.26	1.14	1.37	0.2	11.00	0.15
57	Drain	m61410l	0.12	0.22	0.22	0.4	6.00	0.21
23	Drain	m62305l	1.27	1.14	0.94	0.8	3.00	0.27
53	Drain	d0427	0.05	0.04	0.11	0.37	19.50	0.28
55	Drain	d0429	0.05	0.04	0.12	0.57	13.00	0.35
30	Drain	m64003r	1.42	1.34	1.43	0.2	13.00	0.15
32	Drain	m64005r	1.26	1.14	1.37	0.2	11.00	0.15
71	Culvert	c60902l	0.35	0.32	0.45	-	5.5	-
72	Culvert	cint01	0.34	0.31	0.41	-	6.5	-
13	Drain	m01913	0.04	0.04	0.08	0.45	11.00	0.27
21	Culvert	c2001	0.04	0.05	0.1	-	7	-
18	Drain	d1310	1.64	1.88	0.86	0.52	9.00	0.35
19	Drain	d1311	1.50	1.73	0.97	0.60	8.00	0.24

* Cross Bank

Appendix B Table 1. Continued

Channel Slope (%)	Direction (De.)	Culvert Size (m)	RCW* (m)	RCL* (m)	RCA* (m^2)	Drain Class	Hill Slope (%)	Drain Location	Field Distance* (m)
7	40	-	0.45	65	29.25	6	12	Left	167
-	250	0.5	2	21.5	43	1	7	Left	0
10	64	-	0.43	27	11.61	2	7	Left	-
13	63	-	1.15	126	144.9	1	18	Left	-
-	30	0.3	1.85	87	160.95	4	16	Left	-
10	60	-	0.94	58.5	54.99	1	19	Left	-
-	90	0.4	2	60	120	4	17	Right	90
7	175	-	3.5	25	87.5	1	15	Left	212
12	55	-	1.45	44	63.8	2	20	Left	-
-	125	0.3	1.4	125	169	4	12	Right	98
-	234	0.4	1.5	275	412.5	4	16	Left	-
5	175	-	2.9	37.5	108.75	1	17	Left	-
6	163	-	3	52.5	157.5	1	15	Left	-
2	185	-	1.2	35	42	2	28	Left	178
3	240	-	1	46	46	5	6	Right	96
-	30	0.3	1.2	75	90	4	13	Left	15
-	40	0.4	1.7	47	79.9	2	19	Left	0
1	247	-	0.85	125	106.25	3	14	Right	-
-	70	0.7	1.3	95	123.5	4	24	Right	0
-	105	0.8	2	200	400	1	17	Left	-
2	238	-	1.3	8	10.4	1	10	Right	-
3	130	-	1.1	18	19.8	1	8	Right	-
3	345	-	1	35	35	1	13	Right	-
4	25	-	0.98	12	11.76	5	5	Right	266
1	155	-	1.1	12	13.2	5	4	Left	-
4	56	-	1	15	15	2	5	Right	-
3	245	-	1.6	62.5	100	2	22	Left	62
3	275	-	0.66	19	12.54	5	6	Left	-
4	80	-	1.1	28	30.8	1	8	Right	346
8	65	-	1.1	58	63.8	4	29	Right	67
9	8	-	1.1	24	26.4	1	13	Left	140
5	15	-	1	21	21	2	12	Left	63
4	345	-	1.3	65	84.5	4	21	Right	87
4	342	-	2.7	42	113.4	2	19	Left	0
10	290	-	0.85	48.5	41.225	1	17	Left	75
10	330	-	1.55	57.5	89.125	1	16	Left	81
9	8	-	1.1	24	26.4	1	13	Left	140
5	15	-	1	21	21	2	12	Left	63
-	235	0.6	1.2	38	45.6	4	22	Right	0
-	298	0.4	1.2	85	102	4	15	Right	12
5	80	-	1	57.5	57.5	1	26	Left	251
-	275	0.4	2.5	67	167.5	1	20	Right	0
11	50	-	0.72	65.00	46.80	1	16	Left	52
9	66	-	1.10	34.00	37.40	1	8	Left	45

*Field measured road-to-stream hydrologic distance, RCW = road contributing width, RCL = road contributing length, RCA = road contributing area

Appendix B Table 1. Continued

R.G.* Outlet	R.G.* Code	WP Len.*	Elevation (m)	CTI	SPI	Log SPI	Slope (%)	Aspect	Drainage Area (m^2)
No	0	28	587	7	960	7	8	55	4879
No	0	0	604	7	20283.7	9.92	5	247.15	151816
No	0	12.5	576	8	2577	8.00	10	57.00	10510.00
Yes	1	37.5	573	10	3822	8.00	11	59.00	16497.00
Yes	1	0	662	7	3467.4	8.15	16	35.81	8409.48
Yes	1	23	635	10	1826	8.00	16	104.00	6027.00
Yes	1	17	596	7	2646.31	7.88	11	104.45	9647.53
Yes	1	11	643	10	931	7.00	15	95.00	4093.00
Yes	1	36.5	624	7	3233	8.00	12	137.00	6796.00
Yes	1	21	576	7	1815.46	7.50	12	84.51	6036.41
Yes	1	36.5	566	7	4503.78	8.41	14	141.61	13181.20
Yes	1	38	642	10	847	7.00	12	123.00	3309.00
Yes	1	41	642	11	847	7.00	10	123.00	3309.00
Yes	1	18	613	7	659	6.00	9	189.00	3099.00
No	0	22.5	613	7	659	6.00	7	189.00	3099.00
Yes	1	0	575	9	8644.52	9.06	12	113.30	50411.80
Yes	1	0	578	10	3242.84	8.08	12	114.37	30589.60
Yes	1	35.5	612	11	366	6.00	14	233.00	2793.00
Yes	1	34.5	566	8	1564.88	7.36	10	120.26	7209.14
Yes	1	42.5	701	9	10745.7	9.28	11	117.17	38674.80
No	0	45.5	611	7	430	6.00	5	171.00	2537.00
No	0	7.5	571	7	216	5.00	3	92.00	2471.00
No	0	7.5	567	8	533	6.00	5	16.00	4406.00
No	0	0	566	6	346	6.00	3	57.00	4593.00
No	0	0	566	8	46	4.00	1	74.00	1624.00
No	0	1.5	566	8	47	4.00	1	7.00	1600.00
Yes	1	27.5	564	9	511	6.00	15	149.00	2504.00
No	0	0	570	7	645	6.00	2	317.00	13511.00
No	0	7.5	566	7	226	5.00	4	90.00	2121.00
Yes	1	33.5	559	9	1365	7.00	14	68.00	3846.00
No	0	12	604	7	1326	7.00	11	47.00	4745.00
No	0	8.5	593	7	3192	8.00	8	41.00	10938.00
Yes	1	28.5	543	7	3472	8.00	15	305.00	9029.00
Yes	1	36.5	552	11	30867	10.00	8	343.00	159953.0
Yes	1	45	650	10	494	6.00	14	334.00	2311.00
Yes	1	35	643	7	878	7.00	9	351.00	4024.00
No	0	12	604	7	1326	7.00	11	47.00	4745.00
No	0	8.5	593	7	3192	8.00	8	41.00	10938.00
Yes	1	0	525	7	61819.8	11.03	10	284.63	179727.0
Yes	1	0	519	14	290052	12.58	11	321.45	2950920.0
Yes	1	16.5	693	8	1695	7.00	13	87.00	10938.00
Yes	1	9	538	18	587212	13.28	11	180.00	25054400
No	0	14.5	566	8	901	7	13	112	3524
No	0	8.5	562	8	2612	8	10	118	11248

R.G.* = Rill and gulley erosion at the drainage outlet, WP Len. = water pathway length

Appendix B Table 1. Continued

Plan Curvature	Profile Curvature	Tangential Curvature	DEM Shade	X	Y	USCA (m^2)
0.26	0.08	0.02	177	684342	6090058	28
-2.68	-0.01	-0.1	183	682168	6091909	20
-1.910	-0.140	-0.190	176	684477	6090055	40
-1.910	-0.050	-0.180	176	684536	6090033	486
0.691	-0.107	0.112	182	683009	6090979	55114
0.680	0.080	0.080	160	683429	6089018	600
-0.143	0.113	-0.016	162	683481	6091758	2238
1.200	0.010	0.110	166	683364	6088983	178
0.310	-0.060	0.060	144	683453	6088876	200
0.252	-0.044	0.030	164	683646	6091919	198
-0.703	-0.079	-0.095	154	683819	6092113	740
1.140	0.060	0.120	160	683369	6088944	298
1.140	0.060	0.120	160	683349	6088955	283
1.130	0.040	0.100	171	682001	6092094	300
1.130	0.040	0.100	171	681996	6092091	73
-1.564	0.084	-0.107	169	684476	6090818	455
-1.633	-0.057	-0.069	172	684394	6090810	200
3.460	-0.040	0.180	180	681980	6092074	200
-1.247	-0.076	-0.108	165	683955	6092630	260
-1.591	0.125	-0.176	161	682692	6090198	271
0.990	0.150	0.070	170	681959	6092051	86
-0.380	0.140	-0.010	176	683973	6093031	37
2.320	-0.050	0.110	183	683912	6093238	95
-1.090	0.080	-0.030	179	683910	6093297	40
4.620	0.060	0.050	179	683928	6093369	48
22.890	0.120	0.270	181	683961	6093439	20
-0.590	0.290	-0.050	165	684029	6093490	530
-4.240	-0.020	-0.080	184	683848	6093091	40
1.910	0.100	0.080	173	684141	6092924	56
1.010	0.070	0.140	167	684248	6092928	256
1.080	-0.010	0.120	177	683620	6092418	20
-0.500	-0.040	-0.060	179	683627	6092477	20
0.410	0.080	0.060	204	683796	6093567	195
-1.130	-0.060	-0.090	191	684568	6092079	1800
2.470	0.040	0.210	193	682552	6091495	183
1.040	0.010	0.090	192	682547	6091548	196
1.080	-0.010	0.120	177	683620	6092418	20
-0.500	-0.040	-0.060	179	683627	6092477	20
-0.540	0.124	-0.074	198	684621	6092613	187
-9.956	-0.368	-0.391	187	684619	6092602	136
7.230	-0.010	0.450	171	683192	6089880	869
0.000	-0.047	0.000	177	686580	6089778	440
-0.59	0.00	-0.06	162	684641	6089978	76
-0.97	-0.09	-0.09	165	684666	6089971	20
-1.71	-0.09	-0.45	130	682956	6089652	40

Appendix B Table 2. Example of the predicted and field measured road-to-stream hydrologic distance

Drain Code	GridPath	PtraLen	DistMwin	DistWash	Near	Field Distance	Out Hill
1	268	135	268	248	299	167	12
5	168	199	168	148	175	118	16
9	60	76	120	60	182	52	13
10	40	51	100	40	229	45	11
11	20	35	20	20	75	24	26
13	80	146	40	80	69	66	18
15	100	95	100	157	218	63	13
16	20	103	533	313	74	50	10
17	40	182	497	333	235	75	10
24	225	215	237	96	68	212	15
26	281	279	317	281	223	246	29
31	261	242	788	731	228	238	19
36	20	55	677	490	156	27	12
40	225	199	110	168	140	90	5
42	200	203	1193	228	179	178	4
48	180	189	685	180	148	172	3
50	180	168	685	180	169	155	8
51	160	201	617	160	117	167	9
53	270	269	1597	515	205	259	14
56	320	321	1448	320	36	297	20
65	270	495	1628	230	327	251	12
68	20	39	1028	77	113	26	43
69	77	87	948	77	262	65	57
70	68	555	997	28	216	78	46
81	125	132	1133	370	220	129	8
82	117	122	1125	361	223	108	15
87	230	208	597	290	76	216	13
88	128	145	128	108	192	137	15
90	20	17	288	161	76	21	13
91	100	84	377	261	112	94	9
96	313	177	388	113	61	223	8
103	358	365	877	1094	147	329	15
110	525	597	788	245	178	485	13
119	397	467	648	117	205	364	11
125	240	342	468	325	94	257	5
126	60	66	100	241	97	62	12
128	0	1	0	221	208	0	21
129	160	155	188	120	96	137	12
138	366	327	508	426	119	345	7
147	245	302	477	305	140	256	6
160	217	442	377	330	83	252	13
175	225	198	168	140	158	214	13
180	188	245	148	148	24	175	12
184	333	319	585	333	164	274	11
186	100	205	641	40	185	95	14
188	20	12	473	333	201	27	12
189	60	69	117	173	274	55	17
200	273	271	657	813	162	266	5
206	233	219	525	193	219	221	5

Appendix B Table 3. Example of field collected data from the forest road segments

From Node	To Node	Road Segment	Length (m)	Road Type	Road Class	Construction Year	Road Width
397	398	6	646.1	Minor Access	4	1950	4
410	364	8	665.4	Minor Access	4	1950	3.5
251	258	703	118.6	Tracks	5	1960	3.5
692	704	551	292.1	Public Roads	2	0	6.5
266	223	21	509.0	Tracks	5	1950	3.5
698	696	93	57.7	Minor Access	4	1968	4
281	261	510	303.1	Tracks	5	1960	3.5
23	18	339	799.7	Major Access	3	0	5
587	598	467	225	Tracks	5	1975	3
275	253	58	228.2	Minor Access	4	0	4.5
660	663	89	74.1	Major Access	2	1968	6
660	656	92	195.9	Major Access	3	1968	4.5
68	50	568	375.9	Major Access	3	0	5
670	675	94	946.1	Minor Access	4	1968	4
130	124	572	329.8	Minor Access	4	1973	3.5
54	14	342	748.2	Minor Access	4	1965	3.5
690	693	109	81.1	Public Roads	2	0	6
609	619	305	374.3	Tracks	5	0	3
79	70	338	1097.3	Major Access	3	1965	5
23	18	339	799.7	Major Access	3	0	5
166	160	418	76	Major Access	2	1975	5.5
605	468	419	670.6	Major Access	2	1975	5.5
373	384	477	89.5	Minor Access	4	1950	4
233	281	508	584.4	Tracks	5	1960	3
363	353	479	343.7	Minor Access	4	1970	3.5
326	279	480	495.3	Minor Access	4	1970	3.5
312	294	492	492.5	Minor Access	4	1970	3.5
384	404	493	230.1	Minor Access	4	1950	3.5
104	120	313	138.1	Major Access	3	1965	5
420	293	416	1143.5	Major Access	3	1975	5.5
468	420	417	454.8	Major Access	3	1975	5
73	46	24	694.6	Major Access	3	1950	5
80	78	25	200.6	Major Access	3	1950	5
696	687	90	132.4	Major Access	3	1968	5
411	481	301	626.5	Tracks	5	1950	3.5
408	443	126	537.1	Major Access	3	1950	5
612	599	127	240.6	Major Access	3	0	5
426	528	270	569.4	Minor Access	4	0	4
588	595	129	112.5	Major Access	3	0	5.5
595	612	130	288.9	Major Access	3	0	5.5
395	400	131	395.3	Major Access	3	1950	5.5
443	450	132	63.1	Major Access	3	1925	5.5
600	611	466	356.6	Tracks	5	1975	3
521	551	274	179.2	Minor Access	4	0	4
535	533	470	260.4	Tracks	5	1975	3.5
602	579	471	74.3	Tracks	5	1950	3.5
340	304	472	580.3	Tracks	5	1975	3.5
5	1	317	508.1	Major Access	3	0	5
288	327	509	349.8	Tracks	5	1960	3.5

Appendix B Table 3. Continued

Road Use (traffic)	Surface Type	Road Geometry	Cutslope			Fillslope		
			Hight (m)	Slope (%)	Cover** (%)	Width (m)	Slope (%)	Cover** (%)
Occasional	N. Surface*	Crowned	0.55	15	10	0.2	-	-
Occasional	N. Surface	Crowned	1	10	5	0.2	-	-
Occasional	N. S. with ruts*	Insloped	0.75	10	5	0.5	-	10
Moderate	Gravel	Crowned	1.05	15	10	0.95	14	10
Occasional	N. S. with ruts	Outsloped	0.45	10	5	0.9	14	10
Light	N. Surface	Outsloped	0.5	-	10	-	-	-
No Traffic	N. S. with ruts	Outsloped	1.1	18	15	1.2	15	10
Light	N. Surface	Outsloped	0.3	-	-	-	-	-
No Traffic	N. S. with ruts	Crowned	0.50	-	15	-	-	-
Occasional	N. Surface	Insloped	1	12	10	1.4	15	10
Light	N. Surface	Crowned	0.7	7	10	-	-	-
Light	N. Surface	Crowned	0.5	-	10	-	-	-
Light	N. Surface	Insloped	0.75	13	5	0.8	8	10
Light	N. Surface	Crowned	0.5	-	10	-	-	-
Occasional	N. S. with ruts	Insloped	0.9	11	10	0.75	15	10
Occasional	N. Surface	Crowned	1.2	14	15	1.5	13	10
No Traffic	N. S. with ruts	Outsloped	1	10	10	1.2	14	15
Light	N. Surface	Crowned	0.95	9	10	0.4	-	-
Light	N. Surface	Crowned	-	-	-	-	-	-
Light	N. Surface	Crowned	-	-	-	-	-	-
Light	Gravel	Crowned	0.7	10	10	0.3	-	-
Light	N. Surface	Crowned	0.7	10	10	-	-	-
No Traffic	N. S. with ruts	Insloped	1	13	10	0.5	-	10
Light	N. Surface	Crowned	0.65	10	10	-	-	-
Light	N. Surface	Crowned	-	-	-	-	-	-
Light	N. Surface	Crowned	-	-	-	-	-	-
Light	N. Surface	Crowned	-	-	-	-	-	-
Light	N. Surface	Crowned	0.5	-	5	-	-	-
Light	N. Surface	Crowned	0.25	-	-	-	-	-
Light	N. Surface	Insloped	1	7	2	0.35	-	-
Light	N. Surface	Insloped	0.8	5	5	0.25	-	-
Light	N. Surface	Insloped	0.45	-	-	-	-	-
Light	N. Surface	Outsloped	1	10	5	0.5	-	-
Light	N. Surface	Outsloped	1.5	12	5	1	10	-
Light	N. Surface	Outsloped	0.3	-	-	-	-	-
Light	N. Surface	Crowned	2.1	16	15	1.7	19	20
Light	N. Surface	Outsloped	0.25	-	-	-	-	-
Light	N. Surface	Crowned	1.2	13	5	0.95	13	17
Occasional	N. Surface	Outsloped	0.85	10	5	0.35	-	-
Light	N. Surface	Outsloped	0.15	-	-	-	-	-
Light	N. Surface	Crowned	0.2	-	10	-	-	-
Light	N. Surface	Outsloped	1.7	17	10	1	15	10
Light	N. Surface	Outsloped	0.55	-	10	-	-	-
No Traffic	N. S. with ruts	Crowned	0.55	-	18	-	-	-
Occasional	N. Surface	Insloped	0.6	10	5	-	-	-
No Traffic	N. S. with ruts	Outslope	-	-	-	-	-	-
No Traffic	N. S. with ruts	Crowned	0.20	-	5	-	-	-
No Traffic	N. S. with ruts	Outsloped	0.55	-	10	-	-	-
Light	N. Surface	Crowned	0.3	-	-	-	-	-
No Traffic	N. S. with ruts	Crowned	0.25	-	-	-	-	-

*N. Surface = Native Surface, N. S. with ruts = Native surface with ruts. **Burned debris are included.

Appendix B Table 3. Continued

Road Surface Slope (%)	Table Drain	Characteristics of Table Drain		
		Width (m)	Depth (m)	Slope (%)
2	Yes	0.25	0.20	4
6	Yes	0.39	0.32	9
9	Yes	0.28	0.25	6
3	Yes	0.35	0.30	5
1	Yes	0.40	0.38	3
3	No	-	-	-
5	Yes	0.42	0.37	7
1	No	-	-	-
9	Yes	0.41	0.35	4
1	Yes	0.45	0.35	3
9	Yes	0.35	0.25	12
6	Yes	0.40	0.30	6
2	Yes	0.52	0.43	4
3	Yes	0.32	0.23	4
12	Yes	0.46	0.44	13
8	Yes	0.28	0.32	11
14	Yes	0.25	0.18	14
7	Yes	0.35	0.38	9
9	Yes	-	-	-
1	No	-	-	-
1	Yes	0.4	0.23	2
4	Yes	0.45	0.25	5
4	Yes	0.52	0.31	6
28	Yes	0.45	0.35	28
14	No	-	-	-
10	No	-	-	-
9	No	-	-	-
6	Yes	0.5	-	5
19	Yes	0.3	0.25	19
1	Yes	0.55	0.37	2
2	Yes	0.6	0.29	3
3	Yes	0.3	0.32	4
8	Yes	0.25	0.30	10
3	No	-	-	-
5	Yes	0.27	0.18	5
5	Yes	0.48	0.35	7
3	No	-	-	-
2	Yes	0.53	0.29	4
10	Yes	0.37	0.3	5
4	No	-	-	-
3	No	-	-	-
4	Yes	0.44	0.35	7
5	Yes	0.3	0.32	6
4	Yes	0.36	0.3	5
7	Yes	0.33	0.24	7
14	No	-	-	-
9	No	-	-	-
4	Yes	0.35	0.27	6
2	No	-	-	-
9	Yes	0.29	0.3	10

Appendix C: Example of Arc Macro Language Used In This Study

Parts of Arc/Info AML Used for Predicting the Road-to-stream Hydrologic Distance

```
/* Ingrid Takken, February 2003
/* aml to calculate flowlines (using ParticleTrack)
/* These flowlines should go all the way down to outlet/demedge,
/* but they get stuck in the valley's generally...

/* Changes has made for the study area by Houshang Farabi, March
2004

/* aml needs to run in grid
&if %:program% ^= GRID &then &do
  &type This AML must be run from GRID
  &return
&end

/* &term 9999
/* display 9999
/* Dem needs to be filled! If not done yet:
/*&sv dem = dem
/*Fill %dem% demfill sink # flowdir

&sv dem = demfill
&sv flowdir = flowdir

&sv drains = stro_drains
arc build %drains% point
arc addxy %drains%

/* add an identification code for the drains
&if [token [listitem %drains%.pat -info] -find dr_code] = 0 &then
&do
  arc additem %drains%.pat %drains%.pat dr_code 4 8 B
&end
reselect %drains%.pat info $recno > 0   /* to select all rows in
table
calc %drains%.pat info dr_code = %drains%#
clearselect %drains%.pat info


&if ^ [exists aspect -grid] &then aspect = aspect(%dem%)
&if ^ [exists flowacc -grid] &then flowacc =
flowaccumulation(%flowdir%)
&sv valthres = 1250   /* threshold to define valleys

/* calculate a direction map for particletrack
/* this direction is the aspect direction, except for
valleybottoms where flowdirection is used.
fds = con(flowacc > %valthres%, %flowdir%, -10)
fdasp = con(fds eq 1, 90, fds eq 2, 135, fds eq 4, 180, fds eq 8,
```

Arc/Info AML for reclassifying the watershed

```
/* Watershed_reclass.aml
/* November 21, 2004, Houshang Farabi, The ANU, SRES
/* Combines some indivitual sub_watersheds into a unique watershed
/* Usage:Washed_reclass <ingrid> <washed_final>
/* ingrid = an existing watershed grid
/* washed_final = the new watershed grid to be created
/* aml needs to run in grid
&if %:program% ^= GRID &then &do
  &type This AML must be run from GRID
  &return
&end


docell
 if (ingrid == 2 or ingrid == 3 or ingrid == 5 or ingrid == 9 or ingrid
== 11 or ingrid == 12) washed_final = 1
 else if (ingrid == 1 or ingrid == 4 or ingrid == 6) washed_final = 2
 else if (ingrid == 10) washed_final = 3
 else if (ingrid == 13 or ingrid == 14 or ingrid == 15 or ingrid == 18
or ingrid == 24) washed_final = 4
 else if (ingrid == 16 or ingrid == 17 or ingrid == 21 or ingrid == 32
or ingrid == 33) washed_final = 5
 else if (ingrid == 20 or ingrid == 25 or ingrid == 31) washed_final = 6
 else if (ingrid == 22 or ingrid == 23) washed_final = 7
 else if (ingrid == 26 or ingrid == 49 or ingrid == 50) washed_final = 8
 else if (ingrid == 34 or ingrid == 35 or ingrid == 36 or ingrid == 37)
washed_final = 9
 else if (ingrid == 30 or ingrid == 38 or ingrid == 39 or ingrid == 40
or ingrid == 41) washed_final = 10
 else if (ingrid == 42) washed_final = 11
 else if (ingrid == 43 or ingrid == 44 or ingrid == 45) washed_final =
12
 else if (ingrid == 46 or ingrid == 61 or ingrid == 62 or ingrid == 70
or ingrid == 96 or ingrid == 71 or ingrid == 84 or ingrid == 85 or
ingrid == 87 or  ingrid == 88 or ingrid == 9 or ingrid   == 97 or
ingrid == 105 or ingrid == 106) washed_final = 13
 else if (ingrid == 47 or ingrid == 57 or ingrid == 58 or ingrid == 59)
washed_final = 14
 else if (ingrid == 48 or ingrid == 64 or ingrid == 65 or ingrid == 68)
washed_final = 15
 else if (ingrid == 51 or ingrid == 66 or ingrid == 67) washed_final =
16
 else if (ingrid == 69 or ingrid == 74 or ingrid == 75 or ingrid == 82
or ingrid == 83 or ingrid == 100 or ingrid == 101) washed_final = 17
 else if (ingrid == 81 or ingrid == 92 or ingrid == 94) washed_final =
18
 else if (ingrid == 86 or ingrid == 91 or ingrid == 93 or ingrid == 95
or ingrid == 98 or ingrid == 99 or ingrid == 107) washed_final = 19
  else washed_final = 0
endif
```

Appendix D: Model Development Statistics

Statistics for Model 1

Appendix D Table 1. Model summary of logistic regression and the goodness-of-fit (Hosmer and Lemeshow Test) of independent variables against dependent variable (rill and gully on the surface of the road)

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square	Hosmer and Lemeshow Test		
				Chi-square	df	Sig.
1	62.396	.674	.905	4.047	8	.850

Appendix D Table 2. Contingency table for Hosmer and Lemeshow Test

Step 1	*RG = 0		RG = 1		Total
	Observed	Expected	Observed	Expected	
1	25	24.961	0	.039	25
2	25	24.851	0	.149	25
3	25	24.500	0	.500	25
4	23	22.717	2	2.283	25
5	8	10.512	17	14.488	25
6	3	1.338	22	23.662	25
7	0	.104	25	24.896	25
8	0	.015	25	24.985	25
9	0	.001	25	24.999	25
10	0	.000	29	29.000	29

*RG = Rill & gullies on the surface of the roads

Appendix D Table 3. Summary of parameter estimates using logistic regression (variables in the equation)

Variables	B	S.E.	Wald	df	Sig.	Exp(B)
Constant	-16.770	3.309	25.681	1	.000	.000
RCA	.121	.021	31.850	1	.000	1.129
Slope	.395	.120	10.747	1	.001	1.484
CTI	.934	.346	7.282	1	.007	2.545

Appendix D Table 4. Model summary of the variables in the equation and regression (rills and gullies on the surface of the road)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.765(a)	.585	.580	.322	.585	117.275	3	250	.000

(a) Predictors: (Constant), Road Contributing Area, Slope, CTI

Appendix D Table 5. Results of ANOVA (b) for independent variables against dependent variable

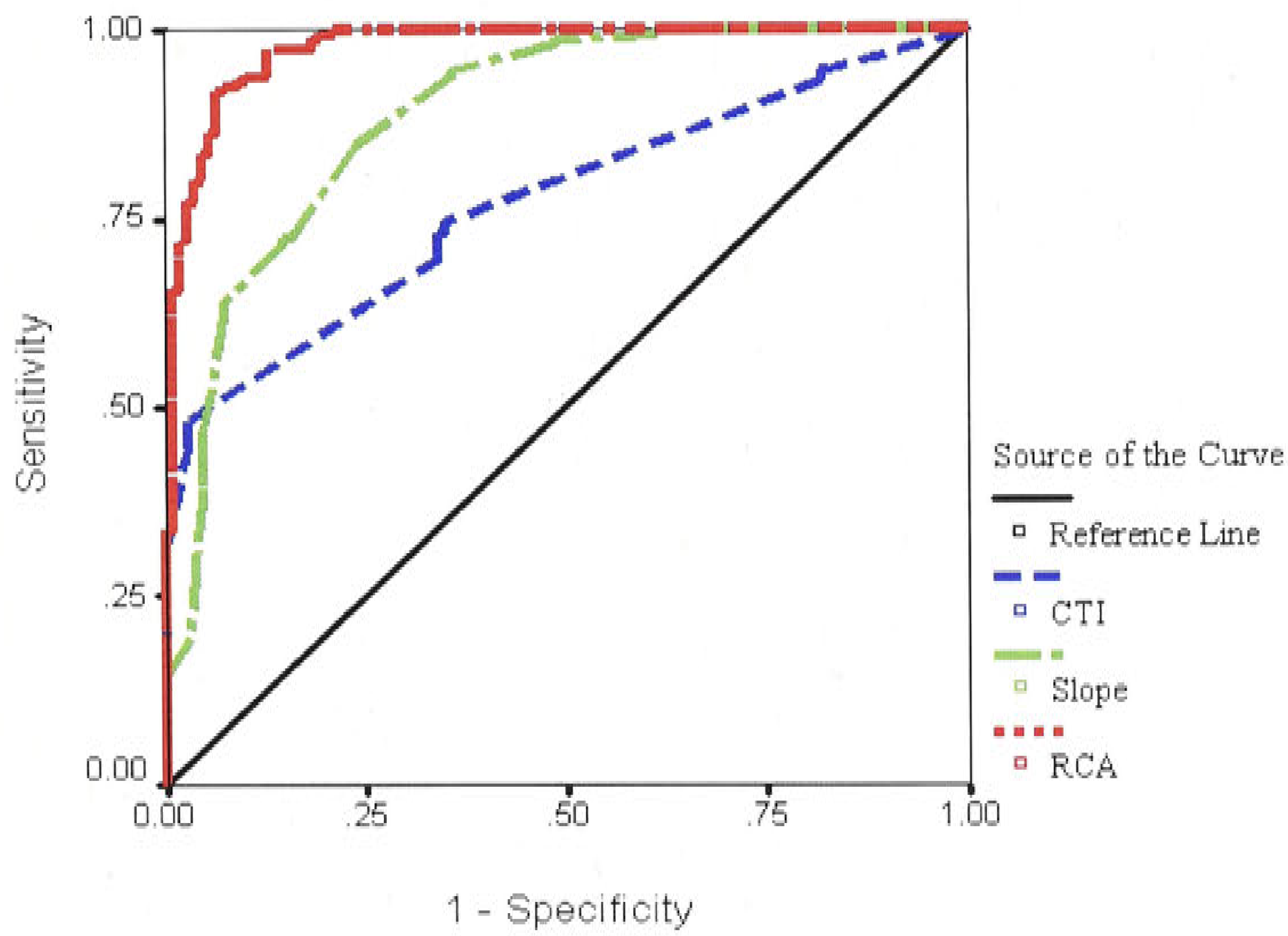
Source of variation	Sum of Squares	*df*	Mean Square	F Statistics	*P* value
Regression	36.376	3	12.125	117.275	.000 (a)
Residual	25.848	250	.103		
Total	62.224	253			

(a) Predictors: (Constant), Contributing Area, Slope, CTI
(b) Dependent Variable: Rill & Gully on the surface of the roads

Appendix D Table 6. Summary of the Coefficients (a)

Model	Variables	Unstandardized Coefficients		Standardized Coefficients (Beta)	t	Sig.
		B	Std. Error			
1	(Constant)	-.573	.097		-5.910	.000
	CTI	.063	.012	.225	5.155	.000
	Slope	.034	.004	.354	7.954	.000
	RCA	.004	.000	.445	10.077	.000

(a) Dependent Variable: Rill & Gully on the surface of the roads



Appendix D Figure 1. Comparison of the ROC curve for the independent variables in relation to the rill and gully occurrence on the surface of the road

Appendix D Table 7. Summary of the area under the curves represented in Figure 1

Test Result Variable(s)	Area	Std. Error (a)	Asymptotic Sig. (b)	Asymptotic 95% Confidence Interval	
				Lower Bound	Upper Bound
RCA	.975	.009	.000	.958	.992
Slope	.889	.021	.000	.848	.930
CTI	.771	.029	.000	.715	.828

The test result variable(s): Road Contributing Area (RCA), Slope, CTI, has at least one tie between the positive actual state group and the negative actual state group. Statistics may be biased.
(a) Under the nonparametric assumption
(b) Null hypothesis: true area = 0.5

Statistics for Model 2

Appendix D Table 8. Model summary of logistic regression and the goodness-of-fit (Hosmer and Lemeshow Test) of independent variables against dependent variable (rill and gully at the outlet of the road drainage structure)

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square	Hosmer and Lemeshow Test		
				Chi-square	df	Sig.
1	50.533	.689	.925	3.659	8	.886

Appendix D Table 9. Contingency table for Hosmer and Lemeshow Test

Step 1	*RG_out = 0		*RG_out = 1		Total
	Observed	Expected	Observed	Expected	
1	25	24.935	0	.065	25
2	25	24.861	0	.139	25
3	25	24.767	0	.233	25
4	25	24.299	0	.701	25
5	6	8.439	19	16.561	25
6	2	1.241	23	23.759	25
7	1	.404	24	24.596	25
8	0	.051	25	24.949	25
9	0	.002	25	24.998	25
10	0	.000	29	29.000	29

RG_out = Rill & Gully at the outlet of the drains

Appendix D Table 10. Summary of logistic regression (variables in the equation) of independent variables against dependent variable (rill and gully at the outlet of the road drainage structure)

Variables	B	S.E.	Wald	df	Sig.	Exp(B)
Constant	-8.980	1.719	27.303	1	.000	.000
RCA	.055	.018	9.643	1	.002	1.056
Hillslope gradient	.227	.093	5.955	1	.015	1.255
USCA	.012	.005	6.238	1	.013	1.012

Appendix D Table 11. Results of ANOVA (b) for independent variables against dependent variable

Source of variation	Sum of Squares	df	Mean Square	F Statistics	P value
Regression	40.625	3	13.542	156.739	.000(a)
Residual	21.599	250	.086		
Total	62.224	253			

(a) Predictors: (Constant), USCA, Hillslope Gradient, Distance, RCA
(b) Dependent Variable: Rill & Gully at the outlet of the drains

Appendix D Table 12. Regression model summary of the variables in the equation and regression for independent variables against dependent variable (rill and gully at the outlet of the road drainage structure)

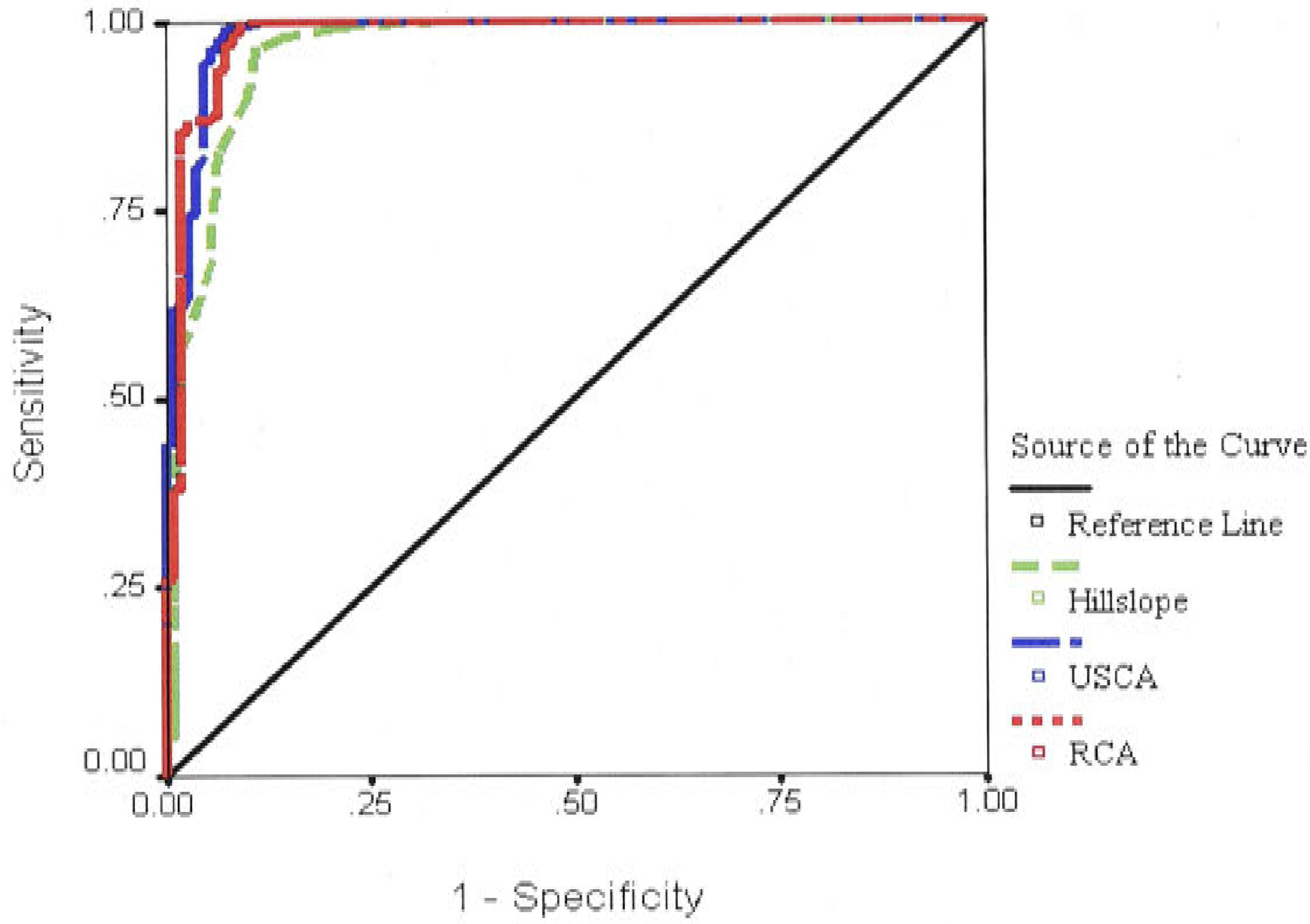
Model	R	R Square	Adjusted R Square	Std. Error	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.808(a)	.653	.649	.294	.653	156.739	3	250	.000

(a) Predictors: (Constant), USCA, Hillslope Gradient, Distance, RCA

Appendix D Table 13. Summary of the Coefficients (a)

Mode	Variables	Unstandardized Coefficients		Standardized Coefficients (Beta)	t	Sig.
		B	Std. Error			
1	(Constant)	-.230	.043		-5.324	.000
	RCA	.004	.000	.457	11.579	.000
	Hillslope Gradient	.031	.002	.525	13.337	.000
	USCA	3.606E-06	.000	.077	2.058	.041

(a) Dependent Variable: Rill & Gully at the outlet of the drains

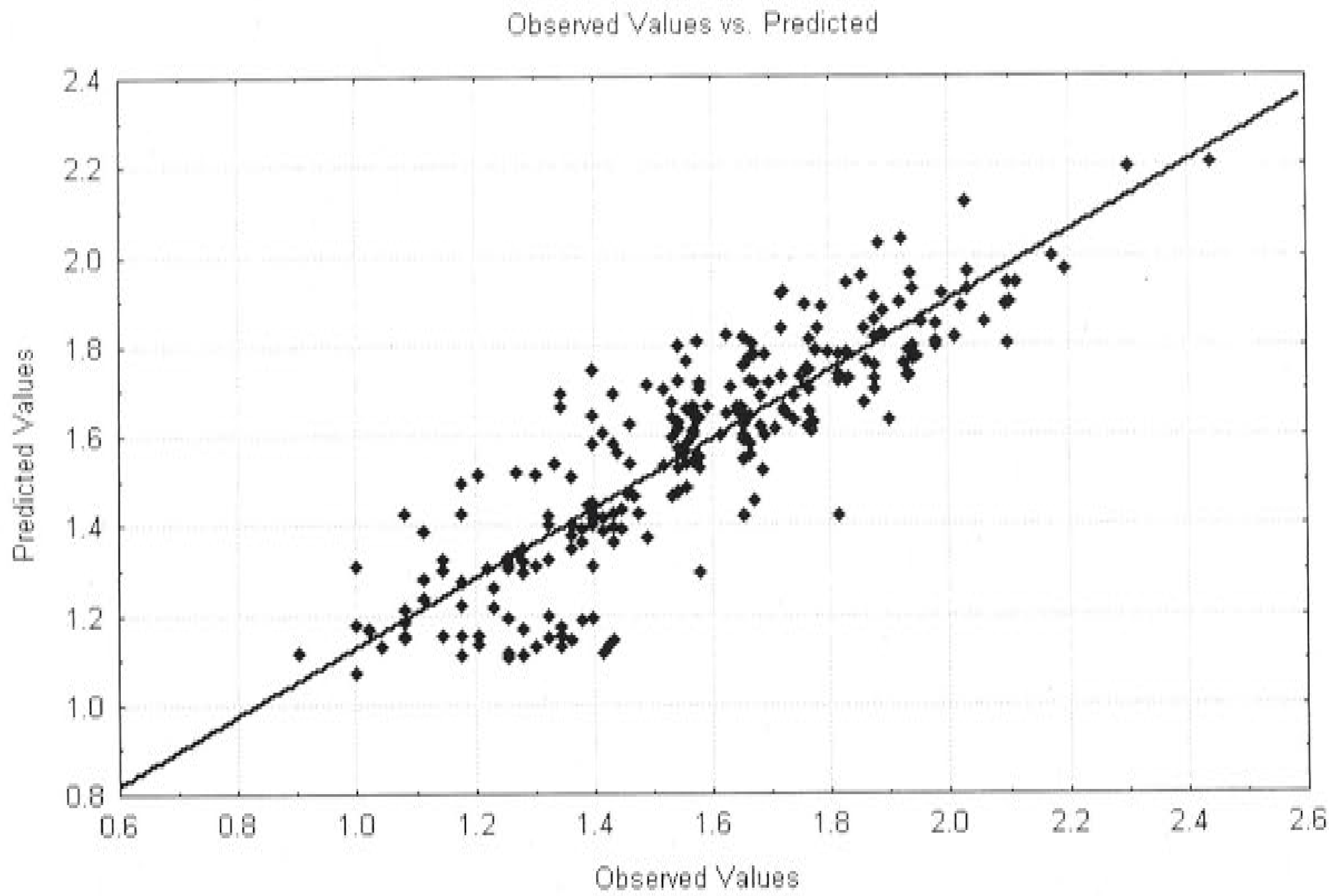


Appendix D Figure 2. Comparison of the ROC curve for the independent variables in relation to the rill and gully occurrence on the surface of the road

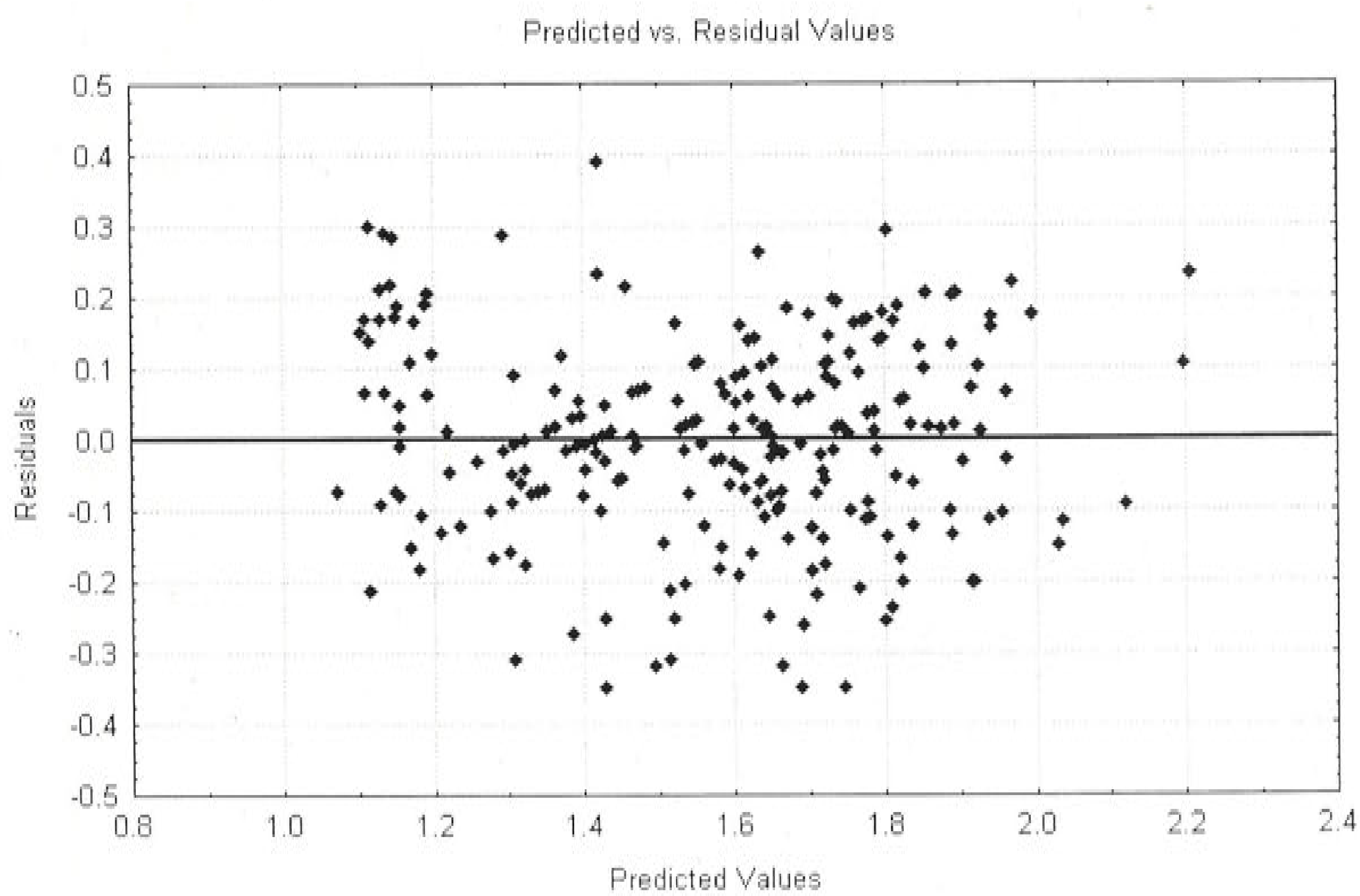
Appendix D Table 14. Summary of the area under the curves represented in Figure 2

Test Result Variable(s)	Area	Std. Error (a)	Asymptotic Sig. (b)	Asymptotic 95% Confidence Interval	
				Lower Bound	Upper Bound
RCA	.983	.008	.000	.968	.998
USCA	.981	.009	.000	.962	.999
Hillslope Gradient	.963	.013	.000	.938	.987

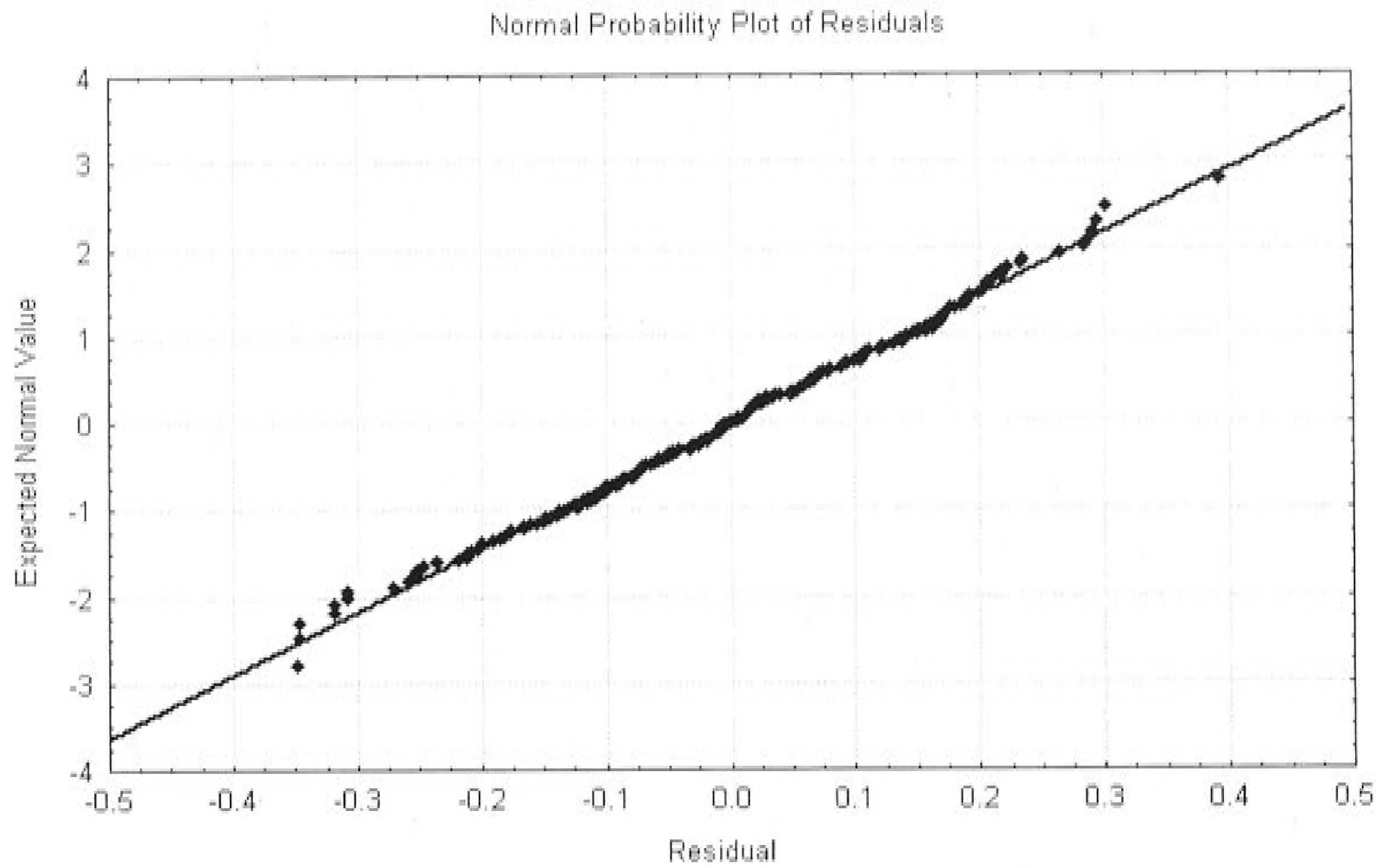
The test result variable(s): RCA, USCA, Hillslope Gradient has at least one tie between the positive actual state group and the negative actual state group. Statistics may be biased.
(a) Under the nonparametric assumption
(b) Null hypothesis: true area = 0



Appendix D Figure 3. Plot of the regression analysis (observed versus predicted values) between the dependent variable and the independent variables (logarithmic transferred)



Appendix D Figure 4. Plot of residuals versus corresponding predicted values (logarithmic transferred)



Appendix D Figure 5. Plots of the regression analysis, normal probability (residuals versus expected normal value) between the dependent variable and the independent variables

Statistics for Model 3

Appendix D Table 15. Model summary of logistic regression and the goodness-of-fit (Hosmer and Lemeshow Test) of independent variables against dependent variable (road-to-stream connectivity)

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square	Hosmer and Lemeshow Test		
				Chi-square	df	Sig.
1	35.191	.710	.950	4.280	8	.831

Appendix D Table 16. Contingency table for Hosmer and Lemeshow Test

Step 1	*Link = 0		Link = 1		Total
	Observed	Expected	Observed	Expected	
1	25	25.000	0	.000	25
2	25	25.000	0	.000	25
3	25	24.993	0	.007	25
4	25	24.921	0	.079	25
5	13	13.617	12	11.383	25
6	1	1.277	24	23.723	25
7	1	.171	24	24.829	25
8	0	.021	25	24.979	25
9	0	.001	25	24.999	25
10	0	.000	29	29.000	29

*Link = Road-to-stream connectivity

Appendix D Table 17. Summary of parameter estimates using logistic regression (variables in the equation)

Variables	B	S.E.	Wald	df	Sig.	Exp(B)
Constant	-12.59	3.436	13.434	1	.000	.000
RCA	.052	.018	8.053	1	.005	1.054
Hillslope	.498	.158	9.895	1	.002	1.645
USCA	.010	.005	4.310	1	.038	1.010
Distance	-.007	.002	10.041	1	.002	.993

Appendix D Table 18. Model summary of the variables in the equation and regression (road-to-stream connectivity)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.804(a)	.647	.641	.299	.647	114.094	4	249	.000

(b) Predictors: (Constant), Road Contributing Area, Hillslope, USCA, Distance

Appendix D Table 19. Results of ANOVA (b) for independent variables against dependent variable

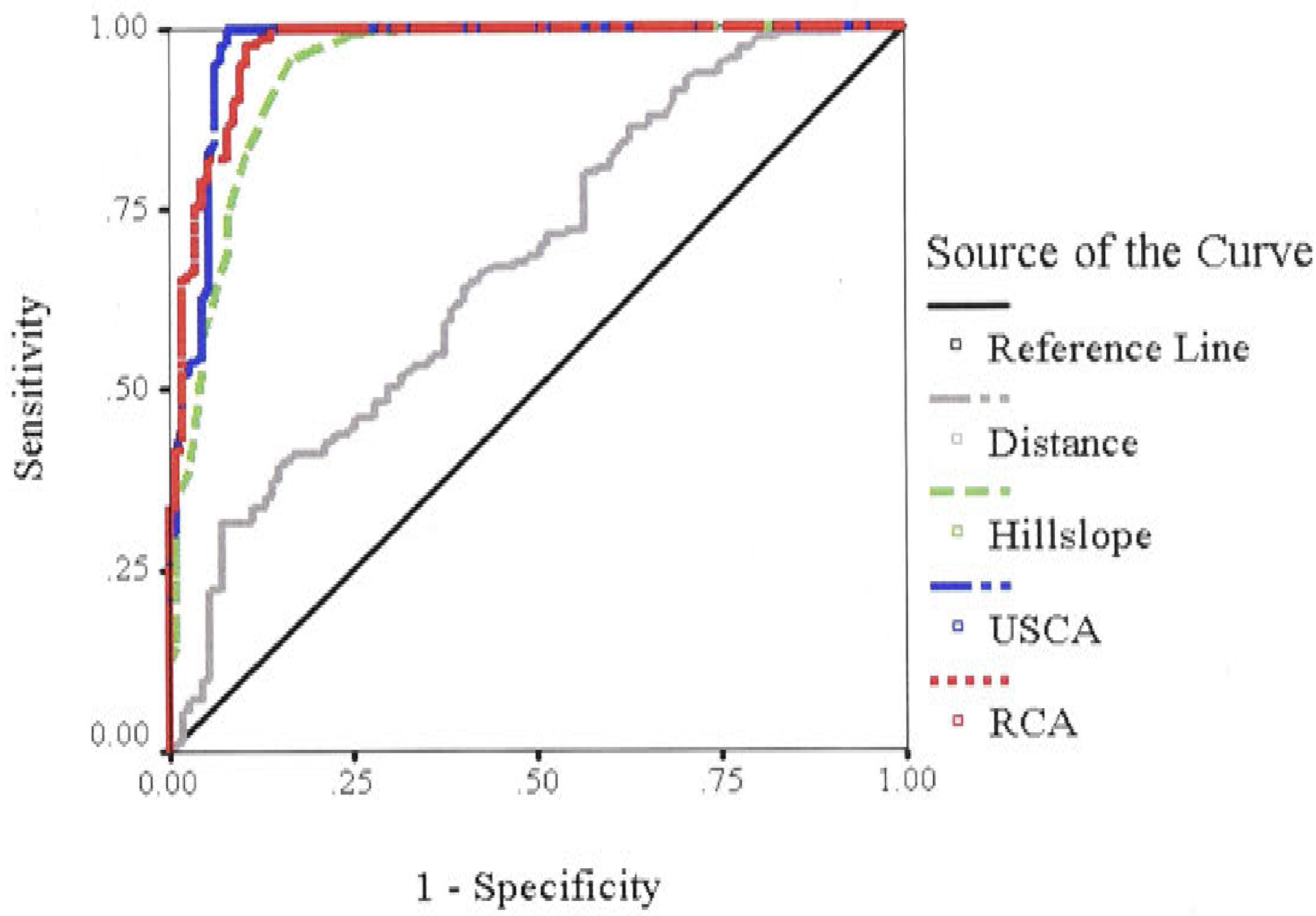
Source of variation	Sum of Squares	*df*	Mean Square	F Statistics	*P* value
Regression	40.921	4	10.230	114.094	.000 (a)
Residual	22.327	249	.090		
Total	63.248	253			

(a) Predictors: (Constant), Road Contributing Area, Hillslope, USCA, Distance
(b) Dependent Variable: Road-to-stream connectivity

Appendix D Table 20. Summary of the Coefficients (a)

Model	Variables	Unstandardized Coefficients		Standardized Coefficients (Beta)	t	Sig.
		B	Std. Error			
1	(Constant)	.141	.061		2.294	.023
	RCA	.003	.000	.404	10.074	.000
	Hillslope	.021	.003	.304	7.629	.000
	USCA	3.647E-06	.000	.083	2.185	.030
	Distance	-.001	.000	-.389	-9.307	.000

(a) Dependent Variable: Road-to-stream connectivity

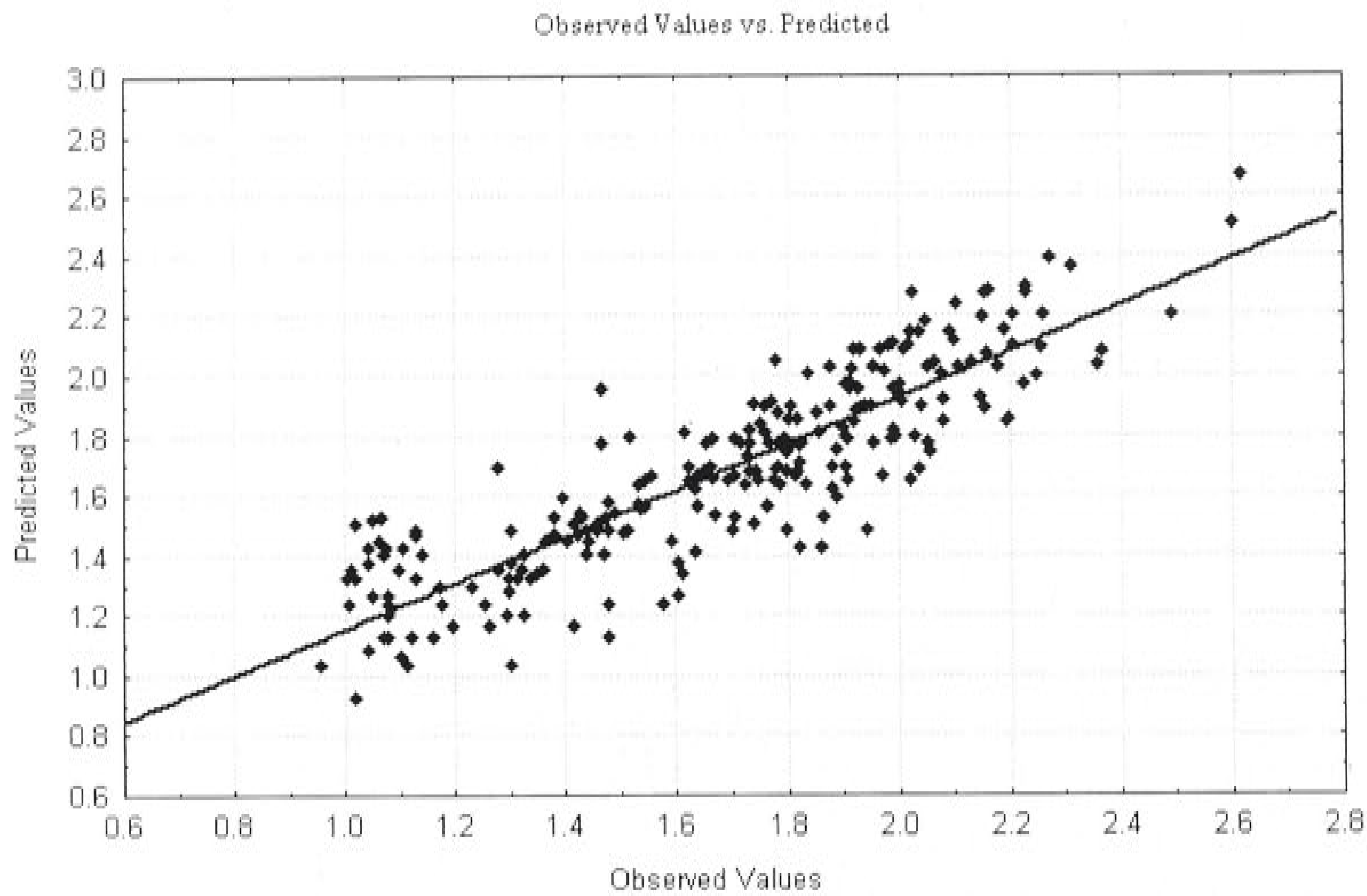


Appendix D Figure 6. Comparison of the ROC curve for the independent variables in relation to the road-to-stream connectivity

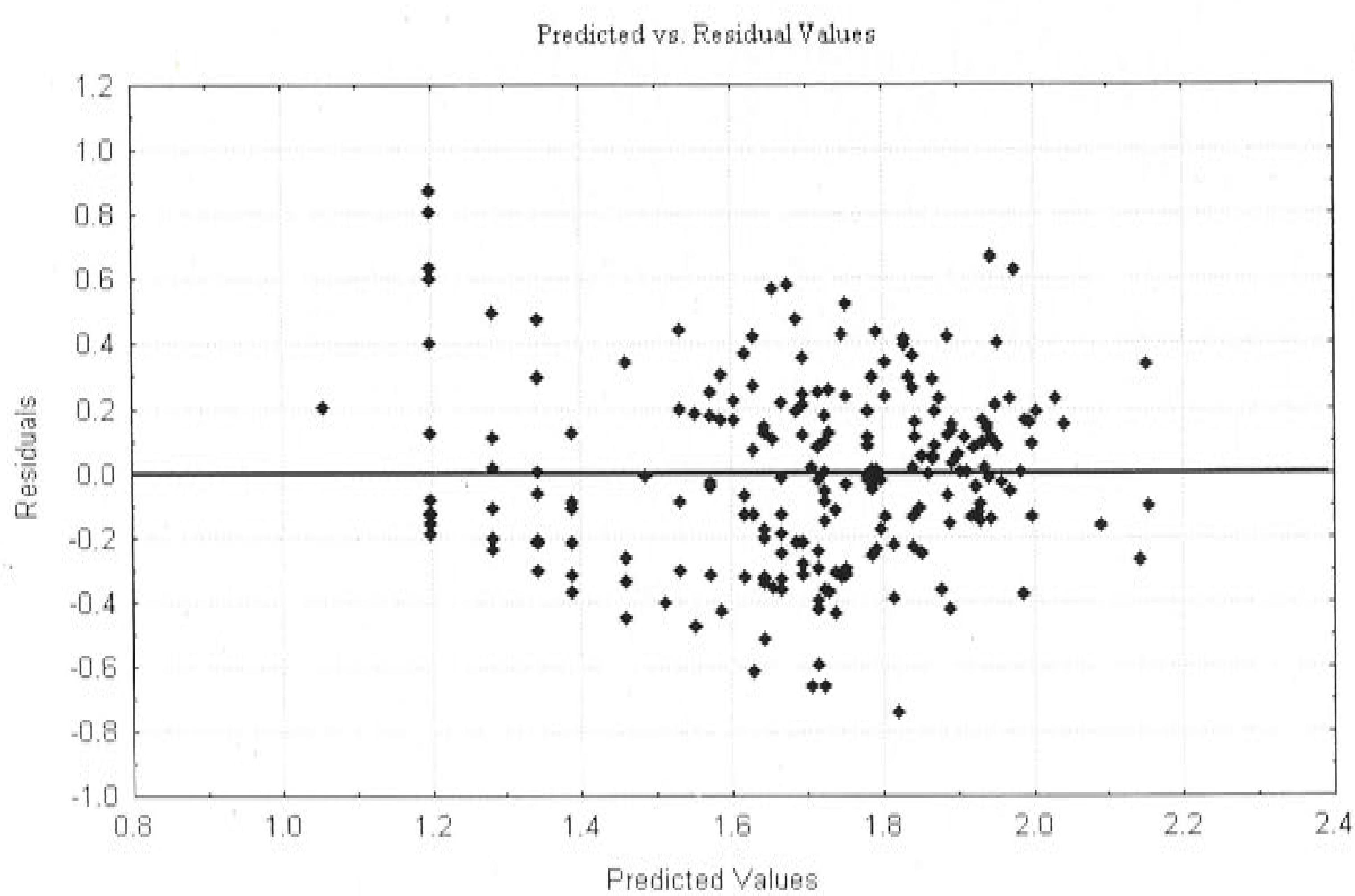
Appendix D Table 21. Summary of the area under the curves represented in Figure 6

Test Result Variable(s)	Area	Std. Error (a)	Asymptotic Sig. (b)	Asymptotic 95% Confidence Interval	
				Lower Bound	Upper Bound
RCA	.972	.010	.000	.952	.991
USCA	.972	.011	.000	.950	.993
Hillslope	.944	.015	.000	.915	.974
Distance	.676	.034	.000	.610	.741

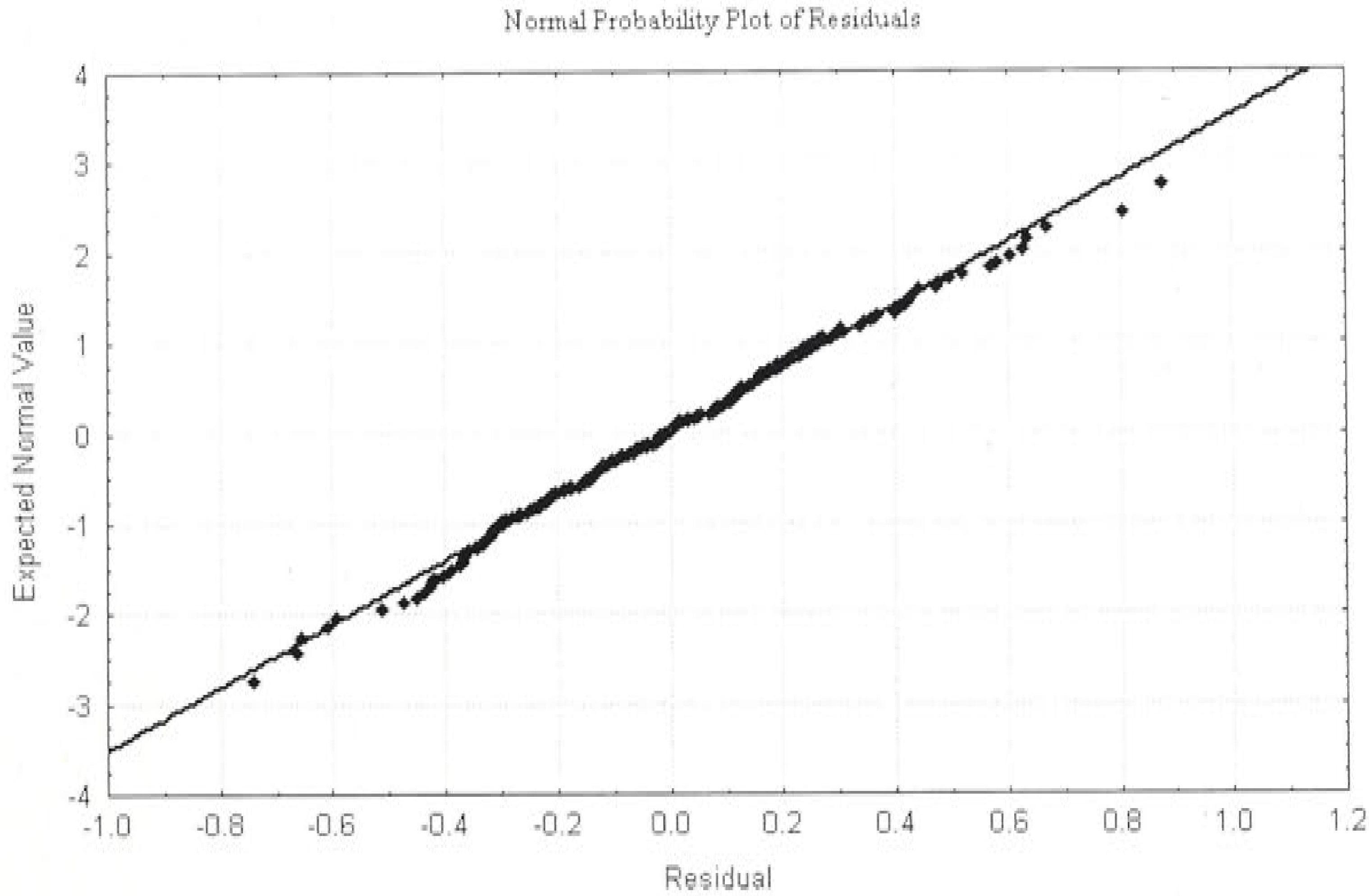
The test result variable(s): Road Contributing Area (RCA), Hillsope, USCA, Distance has at least one tie between the positive actual state group and the negative actual state group. Statistics may be biased.
(a) Under the nonparametric assumption
(b) Null hypothesis: true area = 0.5



Appendix D Figure 7. Plot of the regression analysis (observed versus predicted values) between the dependent variable and the independent variables (logarithmic transferred)

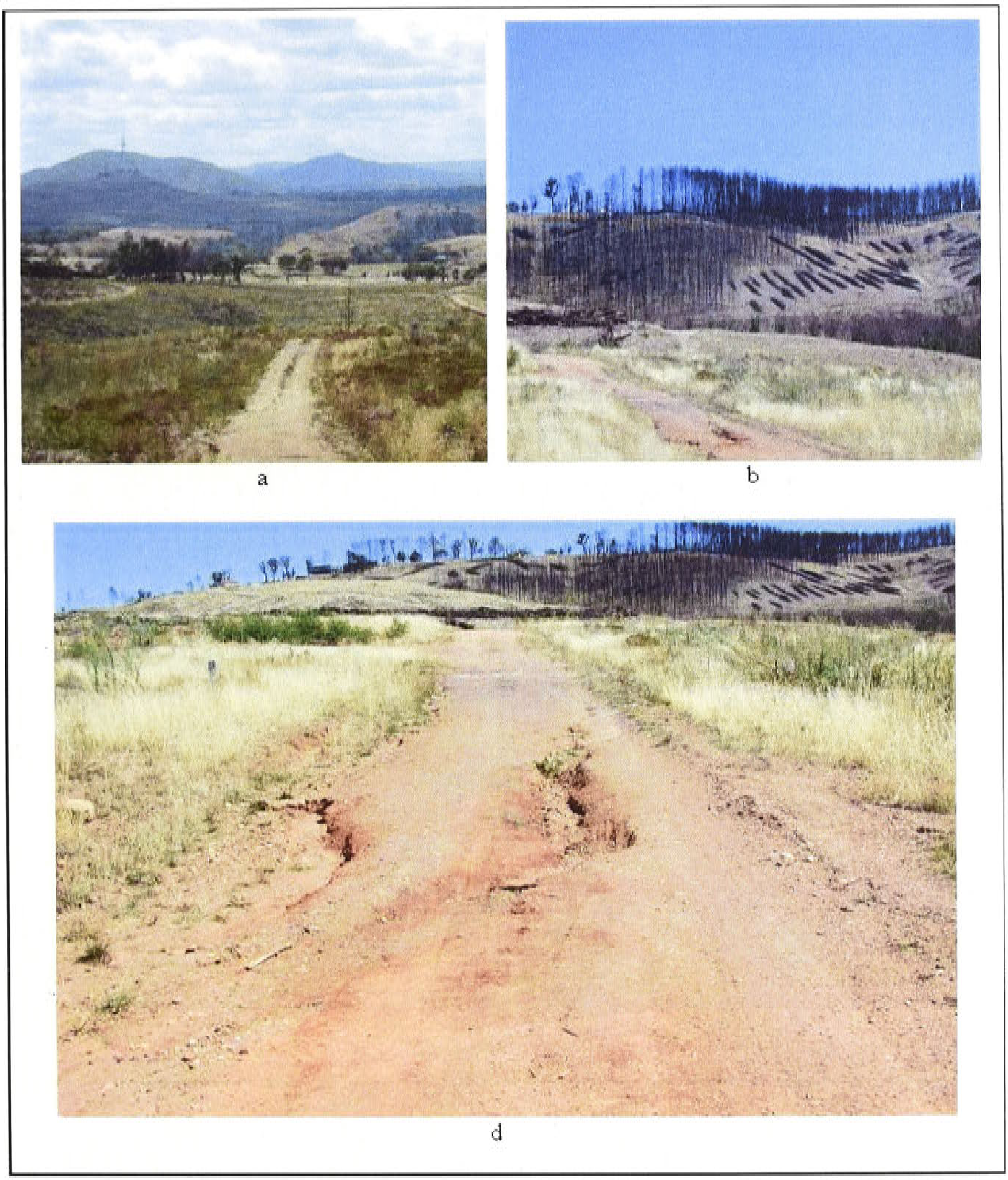


Appendix D Figure 8. Plot of residuals versus corresponding predicted values (logarithmic transferred)



Appendix D Figure 9. Plots of the regression analysis, normal probability (residuals versus expected normal value) between the dependent variable and the independent variables

Appendix E: Views of the Study Area, Showing Forest Roads and Erosion

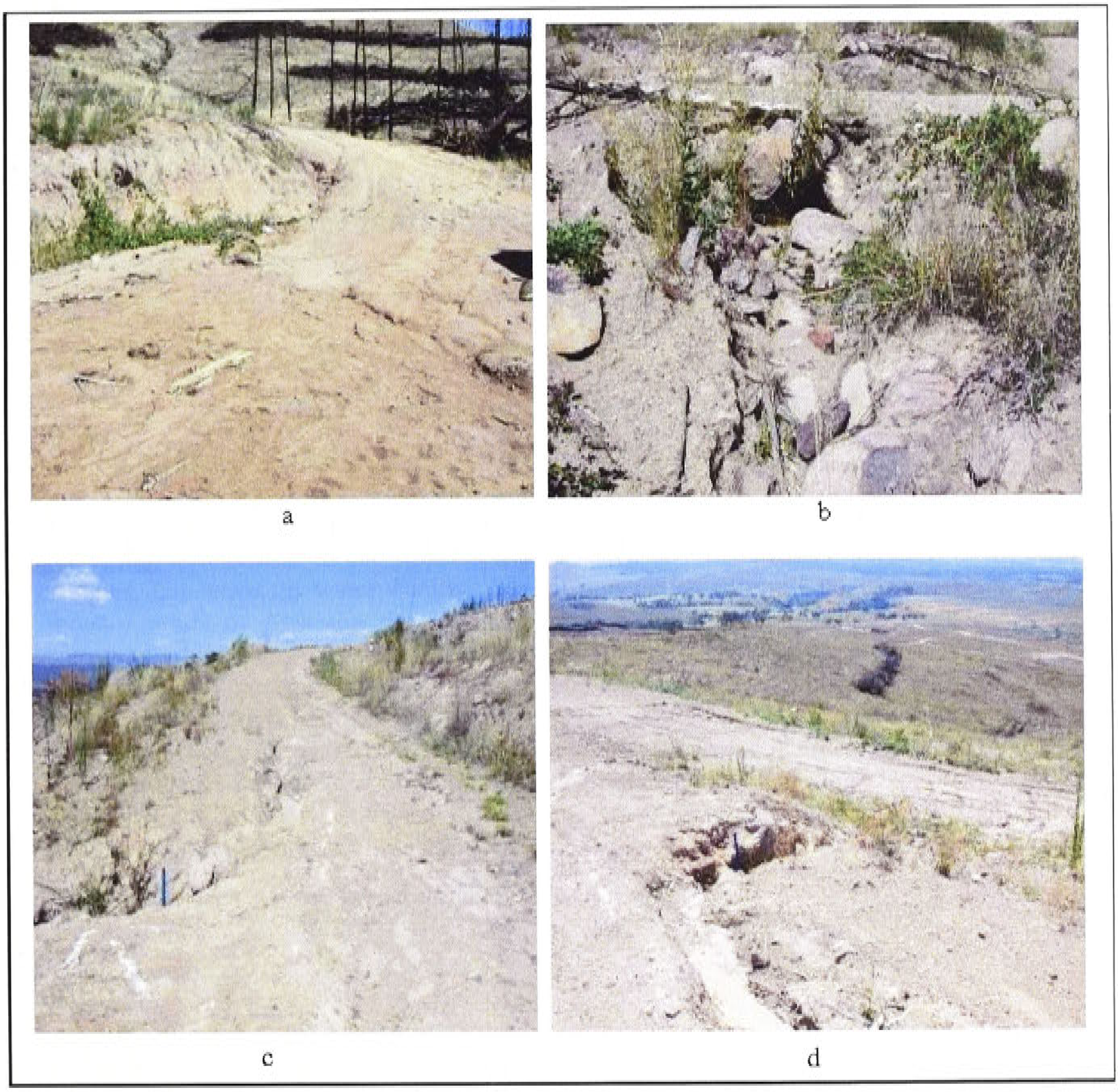


Appendix E Figure 1. General views of the study area (a and b); rill and gully erosion on the surface of forest road (c)

Source: Author's photograph, March/April 2003

Appendix E Figure 2. Erosion and formation: (a) roadside table drain; (b) gully erosion at the inlet of mitre drain; (c) channel formation and bed erosion of the mitre drain

Source: Author's photograph, August/September 2003



Appendix E Figure 3. Rill and gully erosion: (a) on the surface of the road at an intersection; (b and d) on the fill batter and surface of the road at the point of road-to-road connectivity; (c) on the surface of the road because of ditch failure

Source: Author's photograph, March/April 2003

Appendix F: Papers Presented at Conferences

1. Paper presented at the 2nd International Conference on Forest Engineering, Vaxjo, Sweden, 12-15 May 2003.

A "Risk Management" Based Approach to Improve Management of Roads in Forest Plantation

Houshang Farabi, Dr. Robert J. McCormack , and Dr. Ryde James

PhD Student at the ANU/CSIRO, Forestry Operations Research, CSIRO, Australia, Lecturer at the ANU, Canberra, Australia

Summary

Forest catchment areas are known as a major source of high quality water. There is increasing recognition of the impacts that forestry activities, and especially forest road systems, can have on water quality. Design and construction standards of many older forestry roads in Australia do not meet current standards, and these roads can pose abnormally high risks to water quality. A system of assessment based on principles of risk assessment and management is being developed and tested. Techniques drawn from digital terrain analysis are being used to develop indicators of risk. Results from this research have shown that high value of terrain creates some problems in road maintenance. The road was mostly affected where the contribution length, slope gradient and slope length were high. Most rills and gullies were initiated where the value of terrain attributes like CTI in the pixel or neighbouring pixels was high.

Keywords: *Forest Road, Risk, Terrain Attributes, GIS and Water Quality*

Introduction

There is increasing recognition of the impacts that forest road systems have on water quality. Road surfaces are known to be a major source of swift runoff that increases the rate of peak flow and the volume of runoff delivery to drainage systems (King and Tennyson, 1984) which carries sediment and increases turbidity. Forest road construction itself results in water quality impacts(Montgomery, 1994) until soils in disturbed areas have stabilised. Newly built or upgraded roads are usually constructed to meet agreed standards such as a Code of Practice. There are however considerable lengths of older major and especially minor forest roads in Australia that were constructed in the field by local staff without any formal planning. Much of this very extensive legacy of road building does not meet current standards, and poses a higher risk to water quality. Identifying and managing these problem areas is an important issue in improving the management of forest roads. Engineers have been developing methods to meet this challenge. The most general of these is the implementation of forest road management systems; with GIS and GPS as the core enabling-technologies. However, there are still daunting problems because of the road lengths involved, and the frequent lack of recorded information on roads.

This project is founded firstly on ideas from the fields of risk assessment and management and sets out to develop an approach to assist in improving road management. Risk has generally two dimensions: likelihood and consequences. Risk has been defined as a measure of consequences (C) of water quality hazard and hazard probability (P) of impacts occurrence (R= C * P) (QAS, 2002) in the specific area of forest road. The procedures are intended to (a) prioritise expenditure on road data collection and analysis, and then (b) help identify sections of roads at highest risk needing remediation. We used a study site in a Radiata pine plantation managed by ACT Forests near Canberra in Australia. Because of the lack of forest road management details for the study site, we first had to establish a GIS database.

The second group of foundation ideas are drawn from forest hydrology and terrain analysis. Terrain based indices are used to represent the underlying physics of system behaviour and to provide useful tools for identification and determination of the spatial distribution of potential soil erosion areas (eg. following the work of Moore and Wilson, 1992; Gallant and Wilson, 2000). Pallaris (2000) argued that the terrain based indices and STI (Sediment Transport Indices) can provide a useful tool for identifying and determining the dominant spatial patterns of soil erosion, based on the ideas of Moore and Burch (1986b), Moore *et al.* (1988), Moore and Wilson (1992) and Gallant and Wilson (2000). Moore *et al.* (1988) stated that the traditional USLE based approaches to erosion cannot appropriately characterizing ephemeral gully erosion processes. It is important to note that a high value of Compound Topographic Index (CTI) can play a major role in predicting and controlling ephemeral gully erosion away from the main drainage ways (Moore *et al.*, 1988). As a result, the terrain index CTI can be used in drawing erosion risk maps of forest roads where there will be a high alert area on water quality impacts. On the other hand, the high value of SPI (the erosive power of concentrated surface runoff) appears to play a dominant role in controlling ephemeral gully in main drainage ways (Moore *et al.*, 1988).

Methods

The study was carried out in Stromlo Forest, ACT (Australian Capital Territory). This area is located around 10 km west of Canberra and over 2182 hectares (mostly pine plantation) in area. Stromlo Forest has been managed for industrial timber harvesting and forest roads were built about 30-40 years ago. The average elevation of study site is 606 m. asl. The average annual rainfall in the region is 629 mm (Commonwealth Bureau of Meteorology, 2002).

The map of the entire study site was digitised as a digital coverage in a GIS database. Digital Elevation Models (DEMs) and Terrain Attribute maps like CTI, SPI, Curvature, Topographic Aspects and Flow Directions were generated using Arc/Info from digital maps. The entire forest area was divided into hillslope, midslope, and flat areas and several road lines were selected at random for the first examination. The information about the exact location of approximately 30 km of road line, 10 locations of road-to road linkage, 494 mitre drains and cross banks, 51 culverts and 96 rills and gullies on the surface of the road was gathered in the field using a Global Positioning System (GPS). The most common data which were gathered from the field for each culvert, mitre drain or rill were: slope, direction, size, contribution length and width, flow pathway length, evidence of sedimentation, distance between outlet and stream, whether the culvert or mitre drain is working or blocked, runoff delivery to the road prism from upslope areas and the dimensions of the rill or gully. The field data were transferred to GIS and stored as a vector database after necessary correction (Farabi, 2003).

We have used the basic theory of risk assessment, as stated in the introduction, for assessing forest roads in order to identify, classify, rank and analyse the hazard or impacts of forest road systems on water quality (Farabi, 2003). The consequences of risk on water quality was classified into five categories: catastrophic (5), major (4), moderate (3), minor (2) and insignificant (1). The likelihood of risk has also categorised into five levels: almost certain (5), likely (4), possible or moderate (3), unlikely (2) and finally, rare (1). The result of using these categories regarding to risk formula is shown in Table 1.

Table 1: An example of risk matrix

Likelihood		**Consequences**				
		Catastrophic	Major	Moderate	Minor	Insignificant
		5	4	3	2	1
Almost certain	5	E	E	E	H	H
Likely	4	E	E	H	H	M
Possible/Moderate	3	E	E	H	M	L
Unlikely	2	E	H	M	L	L
Rare	1	H	H	M	L	L

Source: Farabi, 2003
(E is extreme risk, H is high risk, M is moderate risk, and L is low risk)

For example, a road management strategy might be that forest roads should not be built on the areas where the risk is extreme (Table 1). In this study we hypothesize that the negative impacts of risk on soil erosion and water quality caused by forest road systems are extreme when the value of terrain attributes are high. The most important aim of this study is to assess how and whether a simple modelling procedure could be a useful diagnostic tool for identifying and evaluating the spatial distribution of erosion-prone areas of forest road, which can be connected to water quality problems in order to draw a risk map.

To do this, the terrain attributes layers were analysed using ArcGIS, ArcInfo, ERDAS and IDRISI software. The vector data (field data) was transferred to raster using this software. The value of each terrain attribute was extracted for each individual road line, culvert, mitre drain and rill and gully location. The extracted data was classified and analysed in order to identify the level of risk of forest road prism. The detailed procedures underlying the risk assessment are now being developed. They address the elements at risk (soil erosion and water quality). These are based where possible on physical models predicting water flow paths and erosion likelihood, evaluated within a 3D terrain context. From these it is intended to identify elements of the road system (eg. culverts and drains) most likely to cause water quality problems. These procedures can be used to assist management in developing more cost effective road maintenance schedules.

Results and discussion

Preliminary results from this study have shown that nearly 10% of culverts and 4% of mitre drains were blocked by stumps or because of technical problems in constriction. About 16% of culverts and 56% of mitre drains only partly worked. It was calculated that about 27% of rill and gully initiation was caused by the lack of proper drainage systems (Farabi, 2003). Results from this research have also shown that high value of terrain attributes like slope, CTI, SPI, contribution length and area create huge problems in road maintenance. For example, about 32% of rills and gullies on the surface of the road have been initiated by high runoff delivery from upslope areas to the road prism. The road was mostly affected where the contribution length, slope gradient and slope length were high. We have found that most rills and gullies were initiated where the value of terrain attributes like CTI in the pixel or neighbouring pixels was high. These results will be used for creating a risk map for focusing on the problems in order to meet the study's objectives.

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2. **Paper presented at the International Congress on Modelling and Simulation (MODSIM2003), Townsville, 14-17 July 2003.**

Risk Based Approach Using Terrain Attributes to Control Water Quality Impacts Caused by Forest Roads

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Abstract: Forest catchments have long been recognised as a source of high quality water. Within forested areas the unsealed forest roads are the main sources of soil erosion and there is increasing concern on the impacts about water quality caused by forest road systems. This problem has been well documented in the research-based literature in the last three decades. The primary objectives of this study are, first, to develop a risk-based approach to predict, control and minimise soil erosion and water quality impacts. Secondly, to assist in the development of more effective management systems to maintain forest roads by assessing maintenance priorities for protection of water quality. This research is being carried out in Stromlo Forest, ACT, where roads were built more than 30 years ago. Surveys have been conducted on the existing roads (and transportation system) focussing on their impacts on soil and water quality. Elements at risk (soil erosion and water quality) were identified using field survey, Digital Elevation Models (DEMs) and Terrain Analysis. The results show that a significant number of rills and gullies were initiated and expanded at locations that had a high CTI value or had a high CTI value in the neighbouring pixel. A threshold based on slope and contributing area did not predict accuracy gully location on the surface of road.

Keywords: *Forest road; water quality impacts; soil erosion; risk assessment; GIS; DEM; terrain*

1. Introduction

Areas covered by any kind of vegetation in general, and forest catchment areas in particular, have long been recognised as a source of high quality water. Water quality impacts caused by forestry activities like timber harvesting and road construction have been a major concern for forest management systems in the last three decades. The issues of soil erosion and water quality impacts affected by timber harvesting and forest roads have long interested both foresters and the public (Adams, 1994). Forest roads, including main roads, logging roads and skid trails concentrate water and increase the risk of sediments being delivered to the streams, with consequences for water quality.

The potential risk of forest roads impacting on water quality mostly depends on the location of the road and terrain attributes such as slope, contribution area, the characteristics of cut and fill batters and technical issues of road construction. Croke and Mockler (2001) showed that contributing length and slope gradient of the hillslope are two main factors of concern for channel initiation and road-to-stream linkage. Moore *et al.* (1988) argued that there is a strong relationship between the distribution of surface soil water content and independent topographic variable aspect and the compound variable ln(A_s) where $A_s = A_b / S$. They also stated that the lack of topographic uniformity like CTI (soil wetness index or soil water content) (A_s) and SPI (the erosive power of concentrated surface runoff) ($A_b * S$) are the two most important factors in determining the location of ephemeral gullies (Moore *et al.* 1988). The processes of surface erosion of forest roads that cause huge problems for water quality are: surface washing by runoff, ephemeral rills or gullies and finally gully erosion caused by water. Terrain attributes like slope, contributing area, flow pathways, curvature (plan, profile, tangential), compound topographic index (CTI), and stream power index (SPI) derived from digital elevation models (DEMs) have been used in this research to identify elements at risk (soil erosion and water quality).

The overall objective of this ongoing research is to provide a risk assessment methodology using the forest road network of Stromlo Forest (as a test area). The aim of this paper is to look at gully erosion risk in the road surface whereby a series of variables are proposed to include in statistical analysis. This paper presents preliminary results from the analysis of data collected so far.

2. Study Area

The study has been conducted in the Stromlo Forest ACT (Australian Capital Territory). The study sites are located approximately 10 km west of Canberra and cover 2182 hectares in area. Elevation in the study area ranges from 432 meters above sea level to 864 meters asl., with an average of 606 meters asl. Most of the study area has been managed for timber harvesting activities over the last 30-40 years. Rainfall in the region is around 629 mm per annum (Commonwealth Bureau of Meteorology, 2002). Stromlo Forest Managed area is serviced by approximately 264 km of unsealed forest roads excluding skid trails and snig tracks. These roads were built more than 30 years ago, which means that they were not built according to the present code of practice. In addition, the area is connected to Canberra by sealed public roads.

3. Materials and Methodology

The map of the entire forest area was digitised and stored as a digital coverage in a GIS (ArcView) database. A Digital Elevation Model (DEM) initially at 40 meters resolution, which later resampled to 20 meters, was used to derive terrain attributes (such as slope, CTI, SPI, aspect). CTI a wetness index or a measure of saturation:

$$CTI = \ln (A_s / T * \tan\beta)$$

Where A_s is the specific contributing area or the local upslope contributing area per unit width of contour line and T is transmissivity when the soil profile is saturated). SPI measures erosive power of flowing water based on the assumption that discharge is proportional to specific catchment area SPI= $A_s * \tan\beta$ (Moore *et al.*, 1993; Wilson and Gallant, 2000).

Along 35 km of unsealed forest roads, which were selected randomly, the exact locations of road lines and all road drainage structures including culverts, mitre drains, cross-banks and push-outs were mapped (Figure 1) using a Global Positioning System (GPS). Also the location of rills and gullies formed in the road surface were mapped (Figure 1). In addition data like slope, direction, contribution length and width, outlet and inlet construction, flow pathway length, distance between outlet and stream, size of culvert, whether the culvert was open or blocked and evidence of sedimentation were gathered for each individual drain, rill and gully.

For the location of the drains, rill and gullies, the attributes from the raster maps (CTI, SPI, Slope) were extracted. The data were used for identifying high-risk areas of forest roads where the road has high potential to generate sediment and deliver it to a stream.

It is assumed that CTI and SPI are the two most important factors in identifying the risk of forest roads to water quality. Therefore, it is hypothesised that the risk of negative impacts on water quality caused by forest roads will be extreme when the values of CTI and SPI are high. The relationship between contributing area and slope of travelway with gully or rill initiation on the surface of road has been examined using a threshold line.

The basic theory of risk assessment was used for assessing forest roads in order to classify, identify and analyse the impacts of forest roads on water quality. The simple representation of the risk equation is a measure of consequences (C) of water quality hazard and hazard probability (P) of impacts occurrence ($R = C * P$) (QAS, 2002). The below tables show the risk categories. The major problems in controlling the probability of the occurrence of risk in forest road management systems are found in levels 5 and 4 (Table1). Achieving certainty about the occurrence of risk is difficult: it needs a long investigation and acceptance of the inevitable high cost is necessary.

Table 1: Risk assessment scoring

Likelihood	Level	Consequence	Level
Almost certain	5	Catastrophic	5
Likely	4	Major	4
Possible/ Mod.	3	Moderate	3
Unlikely	2	Minor	2
Rare	1	Insignificant	1

Catastrophic events and major consequences of risk are sometimes unavoidable. Generally, risk can be ignored where the likelihood is rare or the consequence is insignificant (see Table 1 and 2). In all other situations risk should be investigated. Understanding the exact levels of likelihood and consequences where roads need to be built can help managers to make better decisions about soil erosion and water quality impacts due to the forest roads. Building forest roads where the level of likelihood is high or the consequences are serious is not acceptable (see Tables 1 and 2). Maintenance of these kinds of roads will not only need high investment but it will also be difficult to avoid impacts on water quality.

Table 2: An example of a risk matrix. E is extremely high risk, H is high, M is moderate and L is low.

Likelihood		**Consequences**				
		Catas.	Maj.	Mod	Min.	Insig
		5	4	3	2	1
Almost certain	5	E	E	E	H	H
Likely	4	E	E	H	H	M
Possible/ Moderate	3	E	E	H	M	L
Unlikely	2	E	H	M	L	L
Rare	1	H	H	M	L	L

In the 35 km selected road, the terrain attribute layers like CTI, SPI, slope, up-slope contributing area, forest road location and drain types are used for detailed field surveys. Some scientists have used the same idea for catchment studies. For example, Wemple *et al.* (1996) used three classes of topographic position for their catchment study. Croke and Mockler (2001) used topographic position, road classes, drain type and period of construction in selecting road segments. Road segments for detailed survey were selected using a random sample. In the detailed survey the sample segments of roads were investigated, from which the following information was gathered:

a. Road surface and travelway situation.
b. Road's slope gradient (length and width)
c. The existence of either rill or gully on the surface of the road.
d. Any technical problems in the road drainage system and direct linkage of roads to streams.
e. Contributing areas of each individual drain.
f. Runoff delivery to the road prism from forest.
g. Soil and material types with which road has been surfaced.
h. Road-to-road linkage (runoff or sediment delivery from up-road to down-road).

The field data is used for testing the usefulness of terrain attributes as hands-on indicators of soil erosion and water quality impacts caused by forest road systems. Factors composed of terrain attributes, biophysical variables and forest road management issues affect water quality in areas under forest road construction. The study will reveal the contribution of different terrain attributes along biophysical variables and management issues to the water quality in the further examination. Furthermore, factors played by the terrain attributes (slope, contributing area and CTI in this paper) and technical issues of forest road construction and maintenance are assessed.

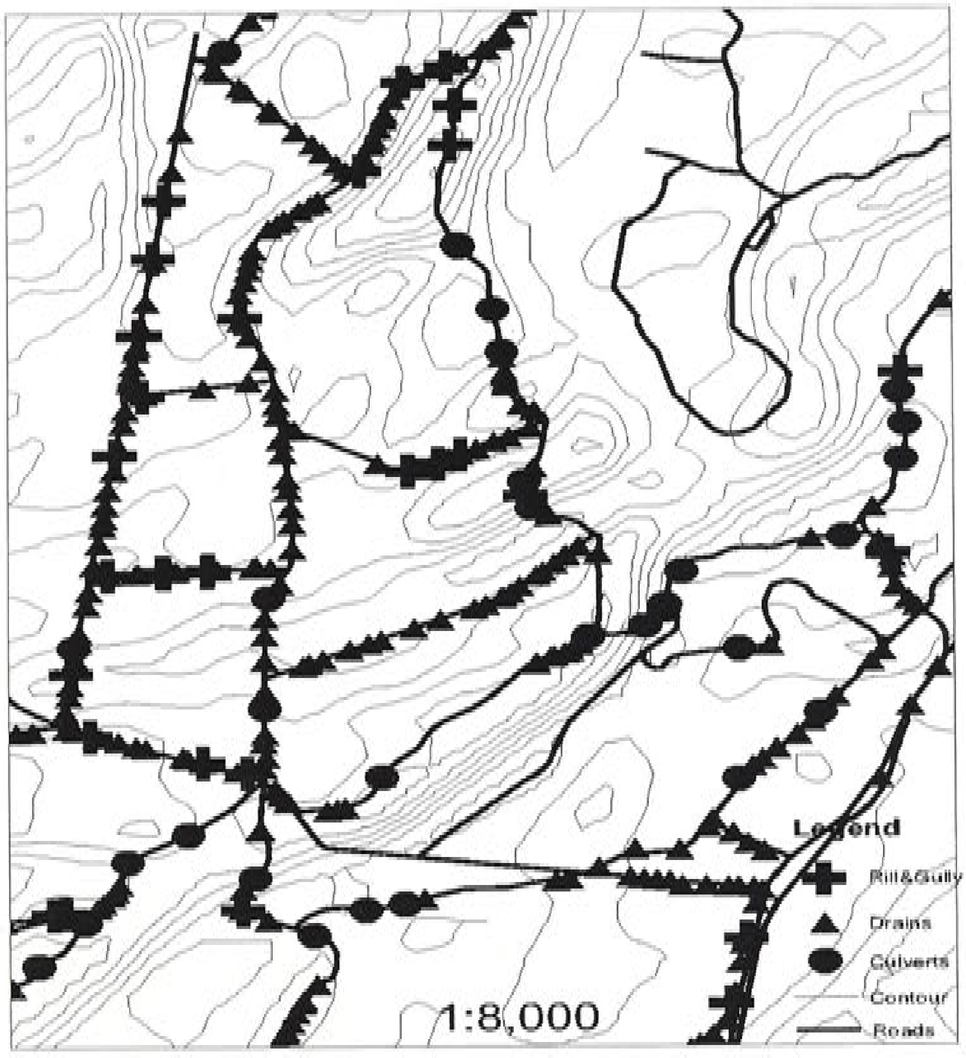

Figure 1: Study area map with road line, contour, mitre drain (triangle), culvert (circle) and rill or gully location (cross icon)

4. Results and Discussion

In Figure 2 the CTI values for the study site are shown. The location of rills and gullies on the road surface are superimposed on the map. Most rill or gully erosion has occurred where the value of CTI was larger than 7 (nearly average values at 7.8), thus supporting the preliminary hypothesis (further examination is required). Although the analysis of this relationship has not yet been finished or finally tested, it is thought that a terrain value like CTI value can play a fundamental role in water quality issues. It was also found that a significant number of rills and gullies were initiated and expanded where the value of the terrain in the neighbourhood pixel was high. For example, as can be seen from Figure 2, most rills and gullies are located very close to the pixels with high values. Extra runoff delivery from neighbouring pixels, especially from the upslope contributing area will increase the risk of rill initiation on the surface of the forest road. Note that other factors like slope, road contribution length and width, technical problems of construction and maintenance of road and drainage are very significant for soil erosion (e.g. gully erosion) and water quality problems. About 27% (26 out of 96) of rill and gully initiation was affected by lack of a proper drainage system and nearly 32% (31 out of 96) of rill and gully initiations were affected by high runoff delivery from the upslope area to the road prism. Slope gradient and slope length of upper hillslope were the two main factors in delivering runoff to the surface of the road, with other factors like contributing area also playing a main role.

Stromlo forest roads are supported mostly by mitre drain systems to control road surface runoff. About 57% (282) of mitre drains had no technical problems from building. Approximately 4% (11) of drains were blocked by stumps and nearly 51% (145) only partly worked in passing runoff out from the road prism. It has been calculated that only 37% (184) of mitre drains worked properly, 56% (277) of them working partly and 7% (33) of drains were blocked. Therefore, road surface and lower drains will be affected by extra runoff delivery from mitre drains which are blocked or are not working properly.

The culvert is another drainage system that protects roads against runoff flowing on the surface of road. Nearly 10% (5) of culverts were blocked by sediment deposition and debris and about 16% (8) of them only partly worked because of technical problems in building and sediment or debris deposition. Outlet and inlet construction is very important to avoid sediment deposition and gully initiation in the ground below where water falls from the outlets of culverts. Nearly 83% (42) of culverts did not have any kind of construction at the inlet and outlet. About 3.9% (2) of outlets and inlets were constructed of concrete and 13.7% of stone or wood. Most blocked culverts and culverts that were partly working were located where the upslope contribution length, slope and area were relatively high.

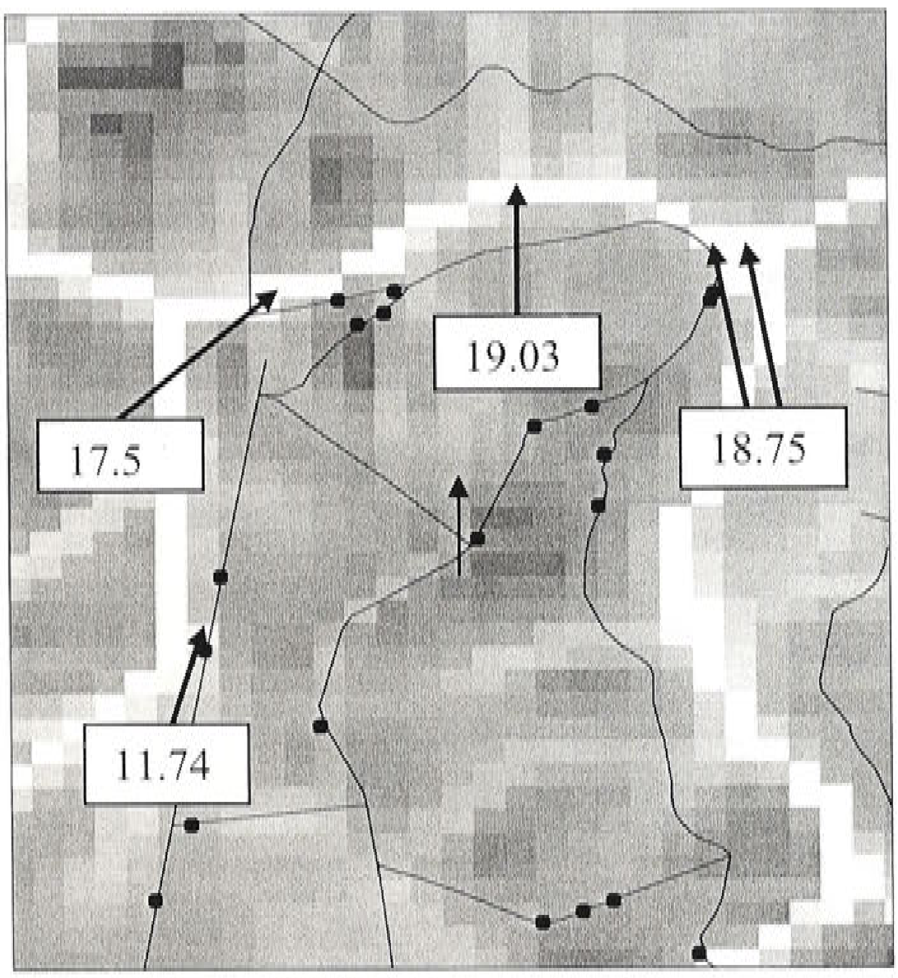

Figure 2: Compound Topographic Index of study area with the location of road layout (black line) and rill or gully location on the surface of the road (black dot icon) (Scale 1:5000)

It has been found in the preliminary analysis of the field data that there exists a strong relationship between high values of terrain attributes like CTI, SPI, slope length, upslope contributing area and curvature with rill or gully initiation on the surface of forest roads in the study area.

Therefore, a risk map of forest roads can be extrapolated by knowing the factors effecting soil erosion and water quality. Although this extrapolation results from the interaction of many factors, one causative variable can be taken at a time (Pallaris, 2000). Contribution length, contribution area, slope length, road layout location, drainage distribution, drain spacing, height and length of batters, slope of batters, road-to-road linkage, road-to-stream linkage, technical problems of road prism, type of soil and material with which the road has been surfaced, runoff delivery from upslope area to road prism and hillslope slope at the outlet of drainage systems are the main factors affecting soil erosion and water quality in forest road systems.

5. Conclusions and Further Work

This study examined 35 km of road line with 545 drainage systems and the location of 94 rills and gullies on the surface of the road and found that the majority of rill and gully erosion points had occurred where the values of terrain attributes were high. Although technical problems of drainage systems (lack of proper drain spacing and construction) also played an important role in terms of initiation of gully erosion, runoff delivery to road prism because of high values of terrain was the major cause of gully initiation. The author replicated the methodology of some previous studies such as Croke and Mockler (2001), Pallaris (2000), Wemple *et al.* (1996) and Montgomery (1994). As can be seen from Figure 3, a threshold based on slope and contribution area did not predict well gully location on the surface of road. Although gullies were initiated at most points where contribution area and slope gradient were high, this figure cannot be used as a good indicator of gully development on the surface of roads. Therefore, gully or rill initiation will be effected by other variables. The effects of other terrain attributes will be examined in further investigations in order to meet the study's objectives.

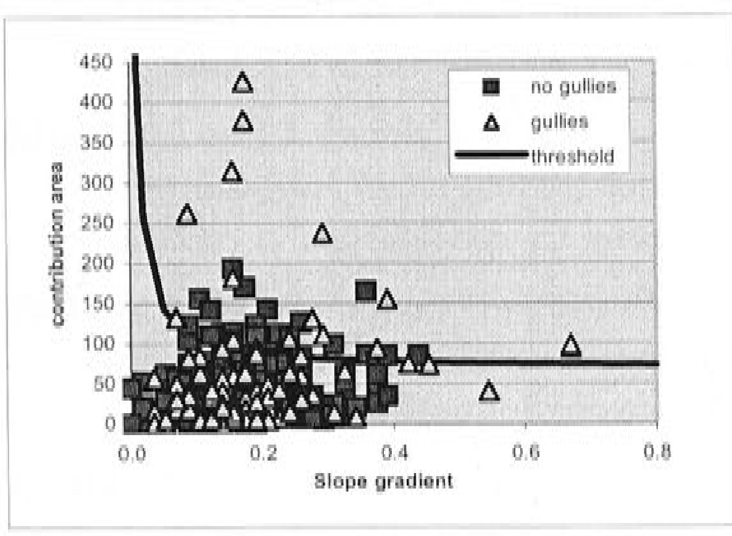

Figure 3: Fitted threshold curve separated gully and non-gully on the surface of road

The preliminary results from multiple linear regression model shown that there is no a strong linear relationship between CTI, SPI contribution area and curvatures and initiation riles and gullies on the surface of the roads because of high multi-colinearity between variables. The effects of each factor on soil erosion and water quality impacts in order to create a simple risk method and model for assessing roads will be examined using non-linear models in further investigation.

Acknowledgements

The author gratefully acknowledges the logistic support of the CSIRO Forestry and Forest products and the financial support of University of Gorgan (IRAN) and the ANU Forestry program (SRES). I especially thank Peter Kanowski, the head of SRES. The author thanks Bob (Robert) McCormack (CSIRO), Ryde James (ANU) and Sue Holzknecht (ANU) for scientific and editorial assistance.

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3. **Paper accepted for poster presentation at the 28th Hydrology & Water Resources Symposium, Wollongong, 10-13 November 2003.**

The Effects of Drain-Spacing, and Contribution of Flow Length and Slope of Road on Rill/Gully Initiation on the Quality of Water from Forests

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The forest watershed has long been recognised as a major source of high quality water. The forest canopy and litter are the main factors in controlling runoff and increasing the rate of soil infiltration. On the other hand, unsealed forest roads have long been recognised as a major source of sediment delivery to streams, with consequences for water quality impacts. The water quality problems caused by forest roads have been well documented in the last three decades.

The main objectives of writing this paper are, first, to identify the role of technical problems of forest roads, which cause soil erosion and water quality impacts like the distribution of drainage systems. Second, to identify the relationship between flow contribution lengths, slope and drain spacing with rill / gully initiation, and its consequences for water quality. Finally, to assist in the development of more effective management systems to maintain forest roads in order to protect water quality.

This research is being carried out in Stromlo Forest ACT, where roads were built more than 30 years ago. The main surveys are conducted on the existing forest plantation roads using GPS, focussing on the impacts on water quality caused by sediment delivery to streams from the surface of the forest roads.

The map of the study area has been digitised and Digital Elevation Models (DEMs) and terrain attributes have been created using GIS. Information about the exact location of forest roads, all roads drainage systems like culverts and mitre drains has been gathered from the field using GPS. The contribution road length, width, road travelway slopes and distance to the nearest watercourse were also measured in the field. The GPS data has been transferred to a GIS program for identifying the roads and drainage location. The data has been analysed using a GIS and linear discriminant program. Elements at risk (soil erosion/ rill or gully forming and water quality) will be identified using DEMs and physical information gathered from the forest road in the field.

Primary analysis of data and some research-based literature show that spacing between drains has a fundamental role in the control of runoff from the surface of the forest road. There is a strong direct relationship between contribution area and slope with rill or gully creation on the surface of the road, with consequences for water quality. The result of this examination will be developed as a method for assessing the ability of the existing forest plantation road system to meet its objectives with minimum risk to the environment.

Keywords: Water quality impacts, forest road, soil erosion, rill and gully, risk assessment, DEMs, GIS

4. Paper presented at the 4th Australian Stream Management Conference, Launceston, 19-22 October 2004.

Mitigating the effects of forest roads on water quality by managing hydrological connections

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Abstract

Forest scientists and managers have long been concerned about the potential effects of unsealed forest road systems on both soil sheet erosion and the deterioration in water quality caused by road sediments. To mitigate the negative impacts of soil erosion on stream water quality, it is necessary to understand the hydrological connection between the sediment source and the stream. Thus, knowing how the flow pathway will be affected by the management of the forest road is important for both managers and researchers. Field surveys were conducted to identify locations on forest roads likely to cause soil erosion and reduce water quality. Data on forest roads were collected in Stromlo Forest, ACT, Australia using GPS. Field data, DEM and terrain GIS layers were used as inputs to calculate values of the multi-evaluation criteria used to indicate the likelihood of erosion. The variables were evaluated using logistic regression. This investigation found that the slope and contribution area of the road were the two most important variables influencing the initiation and expansion of rills and gullies that start from the road drain outlets leading to the stream. These variables, together with other terrain variables such as Compound Topographic Index (CTI) and Stream Power Index (SPI), were also found to affect the linkage between roads and streams. Appropriate management of these factors will reduce the negative impacts of unsealed forest roads on the water quality of adjacent streams.

Keywords: Streams, Forest roads, GPS, GIS, Management, Road drainage

Introduction

Unsealed forest road network are recognised as a major source of sediment production in forested catchments, often leading to major deterioration in the water quality of adjacent streams (Croke *et al.*, 1999). For example, previous research has demonstrated that unsealed forest roads contribute a certain amount of the sediment that impacts on the water quality of adjacent streams. Anderson *et al.* (1976) and Patric (1976) argued that unsealed forest road systems contribute most of the sediment delivered to streams from a forested catchment. Reducing sediment delivery to the watercourses in order to mitigate the deterioration in water quality is therefore a major concern in forest road management systems.

Sediment delivery from road to stream requires overland flow connecting the sediment source to the stream. The hydrological connection between roads and streams can be determined by calculating the potential direction and length of the water flow path, its characteristics and its behaviour in passing over the natural ground cover towards the streams. Knowing how management of the forest road will affect the flow pathway is important for both managers and researchers in managing the connection between the source of sediment and streams. Stream management systems include all activities in the watershed that will affect the stream environment and quantity and quality of water. Many researchers over the last two decades have argued that managing the factors that influence the hydrological connection between roads and streams is one of the most effective management actions that can be taken to reduce deterioration of water quality in forested catchments.

New technologies such as GPS, GIS and the capability of computer analysis make this management process (gathering related field data, calculating the necessary factors, analysing and mapping) faster, easier and much more accurate than the old manual methods. Moore *et al.* (1991) and Tarboton (1997) argued that analysing Digital Elevation Models (DEMs) by creating flow direction, flow accumulation, upslope contribution area and specific catchment area grids is needed for hydrological modelling and management. Lyon (2003) noted that GIS applications for watershed management have been developed and successfully applied in a number of watersheds in order to manage factors related to stream changes (such as forest roads). Croke and Mockler (2001) have used some GIS applications and have reported that slope and contribution length are two important factors that can be used as indicators for road-to-stream linkage.

The aim of the research presented in this paper was to find methods that managers could use to reduce the effects of roading systems on stream sedimentation. The method was to describe the features of forest roads, which might indicate the probability of surface erosion, and to characterise the flow path to the watercourse. These attributes can then be linked to the likelihood that sediment would reach the stream in sufficient quantities to cause deterioration in water quality.

Methods and Materials

The study area was in the Stromlo Forest, and contained radiata pines and an unsealed forest road network. The map of the study area was digitised and stored as a GIS layer. The original map of Stromlo Forest Management Area (SFMA) (known as Stromlo Block) was categorized based on forest road layout, age, road characteristics and classes. A Digital Elevation Model (DEM) initially at 20 meters resolution was used to derive the necessary terrain attribute layers and for terrain and network analysis. Slope, aspect, flow direction, stream order, stream networks, Stream Power Index (SPI), Compound Topographic Index (CTI) or Topographic Wetness Index (TWI), curvatures, upslope contribution area and specific catchment area were some of the terrain attributes derived and calculated from the

DEM using ArcInfo, ArcView, and IDRISI GIS software. SPI measures erosive power of flowing water based on the assumption that discharge is proportional to specific catchment area (SPI= A_s * tanβ). CTI is a wetness index or a measure of saturation (CTI = ln (A_s /T*tanβ) where A_s is the specific contributing area or the local upslope contributing area per unit width of contour line and T is transmissivity when the soil profile is saturated) (Moore *et al.*, 1993; Wilson and Gallant, 2000).

Some roads from Stromlo Forest (see study area characteristics) were then randomly selected for sampling and gathering field data. A Differential Global Positioning Systems (DGPS) instrument was used for the field survey and specific field survey forms were designed for recording each road segment. A permanent base station location at the Forestry and Forest Products site in Yarralumla-approximately 8 kilometres east of the study area-was selected for data correction and positioning the road and drainage systems correctly. The field data included road layout, road surface, roadside table drains (ditch), mitre drains, culverts (relief and stream crossing), outlet slope and also distance between roads (at drainage outlet) to stream. Data describing the drainage systems included the exact location, road contribution width and contribution length, slope gradient, direction, dimension of channel, slope of the channel line at the inlet and outlet of channel (that was used for judging of the technical failure of the drains), evidence (rills and channel formation) of erosion and sedimentation, evidence of channel expansion by runoff, and water flow length from outlet of drains to stream are were just some of the data that were collected to describe the drainage systems.

The exact location of the rills and gullies on the surface of roads and at the outlets of drainage systems was mapped by transferring the GPS field data into GIS as vector layers. Gully characteristics such as dimensions, direction, slope, road contribution length, road contribution width, and other factors related to occurrence of erosion (e.g. vehicle ruts), were collected from the selected roads and drainage systems. The field data were then extracted and stored as databases and were generalised for sensitivity, logistic analysis and testing by a threshold value developed by Croke and Mockler (2001). The correlation of each factor with the incidence of rill and gully was tested against both field and extracted data (terrain attributes). The flow and stream networks were also delineated, identified and mapped from DEM using GIS applications. Some of the created and improved GIS layers such as forest roads (age of roads), soil, stream networks, flow pathways, elevation, contribution area, aspects, CTI, SPI, curvatures and distance were also overlayed for final evaluation and to assess the effect of each factor on the rill and gully influences. The information of the layers such as CTI and SPI has been extracted for each drain using ArcInfo commands and then they were analysed in order to find the relationship of each variable and rill and gully occurrence or road-to-stream connectivity.

Field and extracted data were both used to test the usefulness of the variables (such as terrain attributes) as practical indicators of where forest road network need interventions to manage the connection between roads and streams. The extracted terrain attribute data has been examined (comparing individual and group), using a threshold line and sensitivity analysis in order to identify the relationship between those variables and rill and gully initiation.

Study Area Characteristics

The study was carried out in Stromlo Forest Management Area (SFMA) in ACT (Australian Capital Territory) - located approximately 10 kilometres to the west of Canberra city (Figure 1). The study area is a small area in the southeastern corner of the Murrumbidgee River Catchment. SFMA was established in 1915 and plantation continued in the 1930s. The plantation re-established in the 1940s and 1950s after burning by fire events in 1939 and 1952. The climate of the study area is alpine with warm to hot and relatively dry summers and cool to cold winters (Baskin, 1996). The average annual rainfall of the Canberra region is about 629 mm with an average of 108 rainy days per year, the wettest month being October at 65.3 mm and the driest being June at 39.6 mm (Bureau of Meteorology, 2004). SFMA is serviced by almost 264 km forest roads excluding skid trails, mostly constructed between the 1950s and 1970s. The roads do not meet current design and construction standards and may pose abnormally high risks to water quality (Farabi *et al.*, 2003). Geologically the study area is mostly located on the uniform composition of limestone and phyolithic covering almost 88 percent. The major soil type or group are Duplex and Yellow Earths soils (Chromosols, Sodosols and Kurosols) covering almost 98% of the study area.

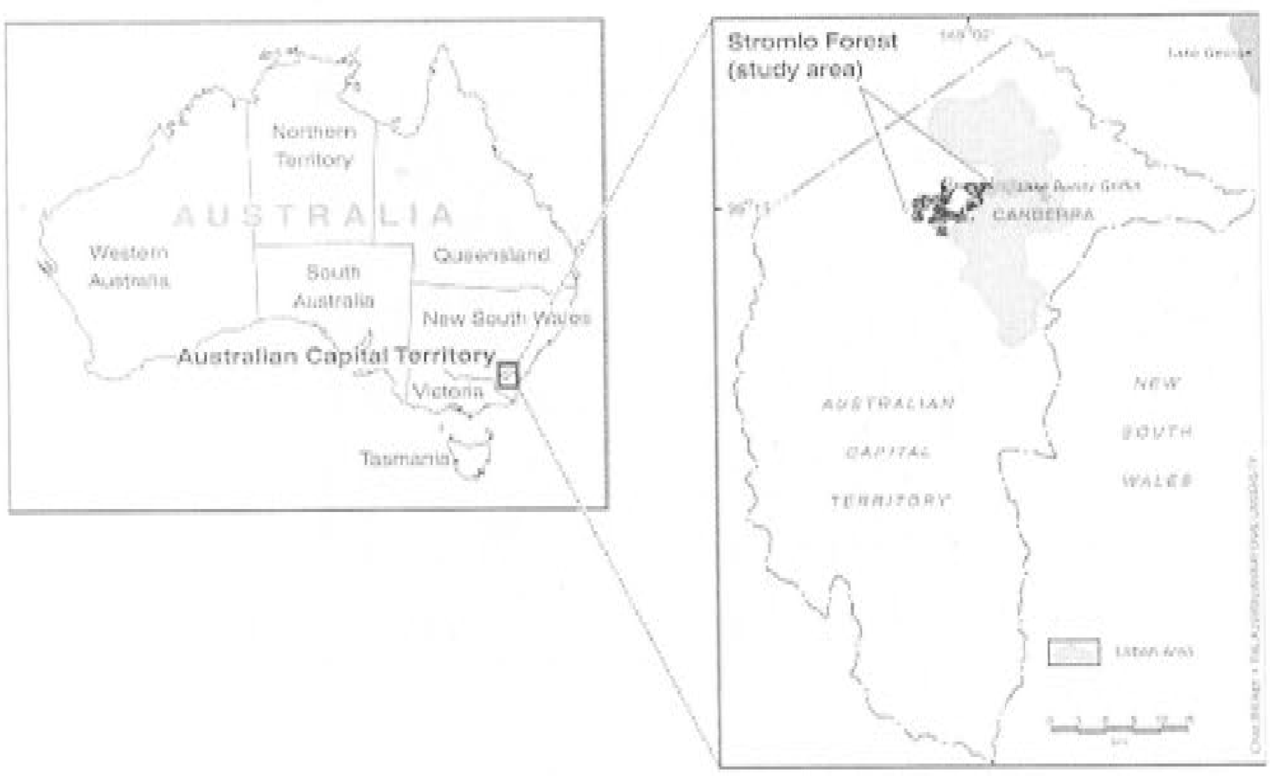

Figure 1: Location of the study area

Results and Discussion

The forest roads of the study area are pre-dominantly drained by mitre drains (604 out of 690, 87%) and relief and stream crossing culverts. Most of previous research (Flanagan *et al.*, 2003, Croke and Mockler, 2001, Megahan *et al.* (2001), Crocke *et al.*, 1999 and Montgomery, D.R., 1994) reported that culvert outlets were the most likely of these features to erode[?]. Field data observation gathered during this study not only supported this statement but also found that mitre drains within greater slope and contribution area are more likely to initiate a new rill or gully or expand the existing rill and gully at the outlets.

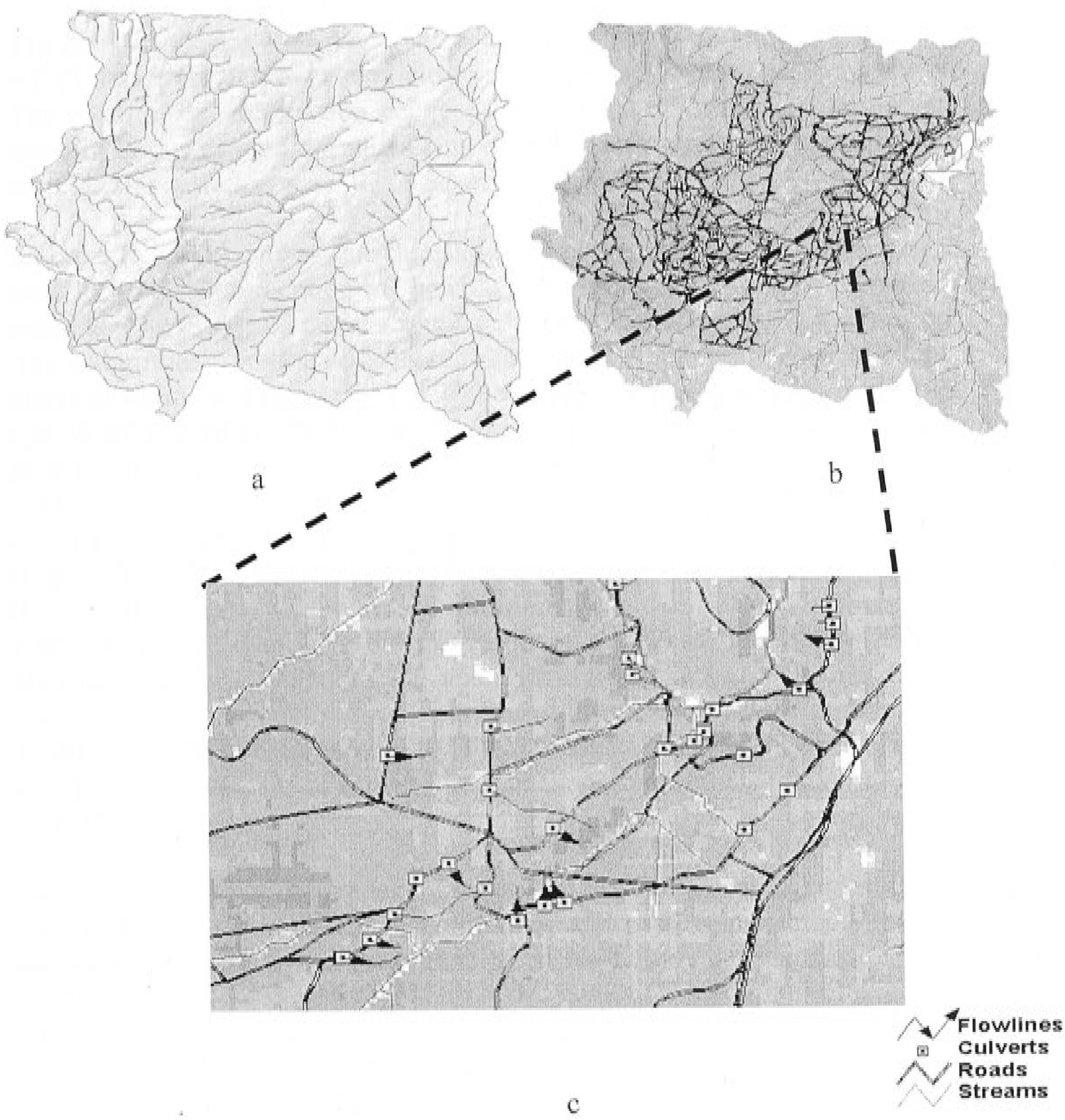

Figure 2. The result of watershed characterisation and stream delineation analysis: a. hillshade of DEM, watershed and stream location, b. CTI map within roads, streams and culverts, and c. Road and culvert positions and the calculated flow direction from culverts

The network, threshold line and statistical analysis results of the study are shown in figures 2 and 3. Figure 2 (a,b,c) shows the results of watershed delineation using the DEM of the study area. Processing the DEM and extracting the necessary data involved "pit and sinks filling correction and computation of aspect and slope". This enabled: computation of flow direction, flow accumulation, upslope contribution area, specific catchment area, stream delineation and order and finally topographic position of the study area for roads and each drain. The area was separated into five basins or sub-watersheds according to their drainage features. Figure 2a shows the hill shade of the study area DEM with sub-watersheds and the exact location of the streams on the landscape. The flowlines from the culverts and the position of the culverts in relation to the road and the road prism on the landscape; especially their position compared with the stream networks that have been mapped in Figure 2c. This same process was repeated for all mitre drain and rills and gullies.

The comparison has shown a strong relationship (correlation coefficient $r = 0.82$, R squared $= 0.67$ and $P < 0.000$) between field-measured hilslope and hillslope derived from the DEM. The result of the comparison between field-measured distance from the outlet of drains to streams and calculated distance using ArcGIS has even shown a stronger relationship with correlation coefficient $r = 0.93$, R squared $= 0.86$ and $P < 0.000$).

Figure 3 (a and b), shows that threshold curves based on slope and contribution area can be used to predict the location of the rills and gullies at the outlets of both mitre drains and culverts. The threshold curve for mitre drains (Figure 3a) shows that more than 90% of the rills and gullies were located where the road contribution area and hillslope gradient at the outlet of drains were greater than 100 m^2 and 30% ($\tan \theta > 0.49$) respectively. There were always rills or gullies present at the outlet of mitre drains when the contribution area was greater than 150 m^2 or the hillslope gradient was more than 50%. For the culverts, a contribution area of greater than 150 m^2 influences most rill and gully initiation at the outlet of the culverts while slope plays a less important role for rill and gully initiation (Figure 3 b). Very few rills and gullies occurred at the outlets of the drainage systems (mitre and culverts) with a contribution area less than 50 m^2. In this situation even slope gradients greater than 40% did not result in a gully initiation from the outlets of drains. Statistical analysis (fitted model and sensitivity) showed a strong relationship between slope gradient and contribution area with the initiation of rill and gully at the outlets of drainage systems (R-Squared = 0.70, $P < 0.001$). This relationship increases when other variables such as CTI, SPI, plan and tangential curvatures are also included; R-Squared = 0.95, $P < 0.0001$.

As well as improper drain spacing (contributing area too high), improper construction was also an important factor causing initiation and expansion of the rills and gullies on the surface of the roads and at the outlets of the road drainage systems. Commonly observed in the field survey, was drainage failure because of technical problems such as installing drains in the wrong position, building too small a size, incorrect sloping and blockage by debris. Preliminary results based on design classification (2 groups- good and bad building- and each group sub-divided into 3 levels working, partly working and blocked) show that about 40% of the drains have at least one of those technical problems. Turbit pools at the outlets of drains, forming the drain channel, sediment slugs in the channel bed and also large debris and slugs in the bed and at the bottom of gully initiated from the outlets toward streams were just some of the field evidence of the impacts of road drainage systems. This also provides evidence of road runoff causing stream sediment and deterioration to water quality. This supported the previous study by Croke and Mockler (2001) using a threshold based on two variables (hillslope gradient and contribution length or area) for separating channelled and non-channelled flowpath where Figure 3 a, b, and c successfully separated the gully and no-gully and road to stream linkage.

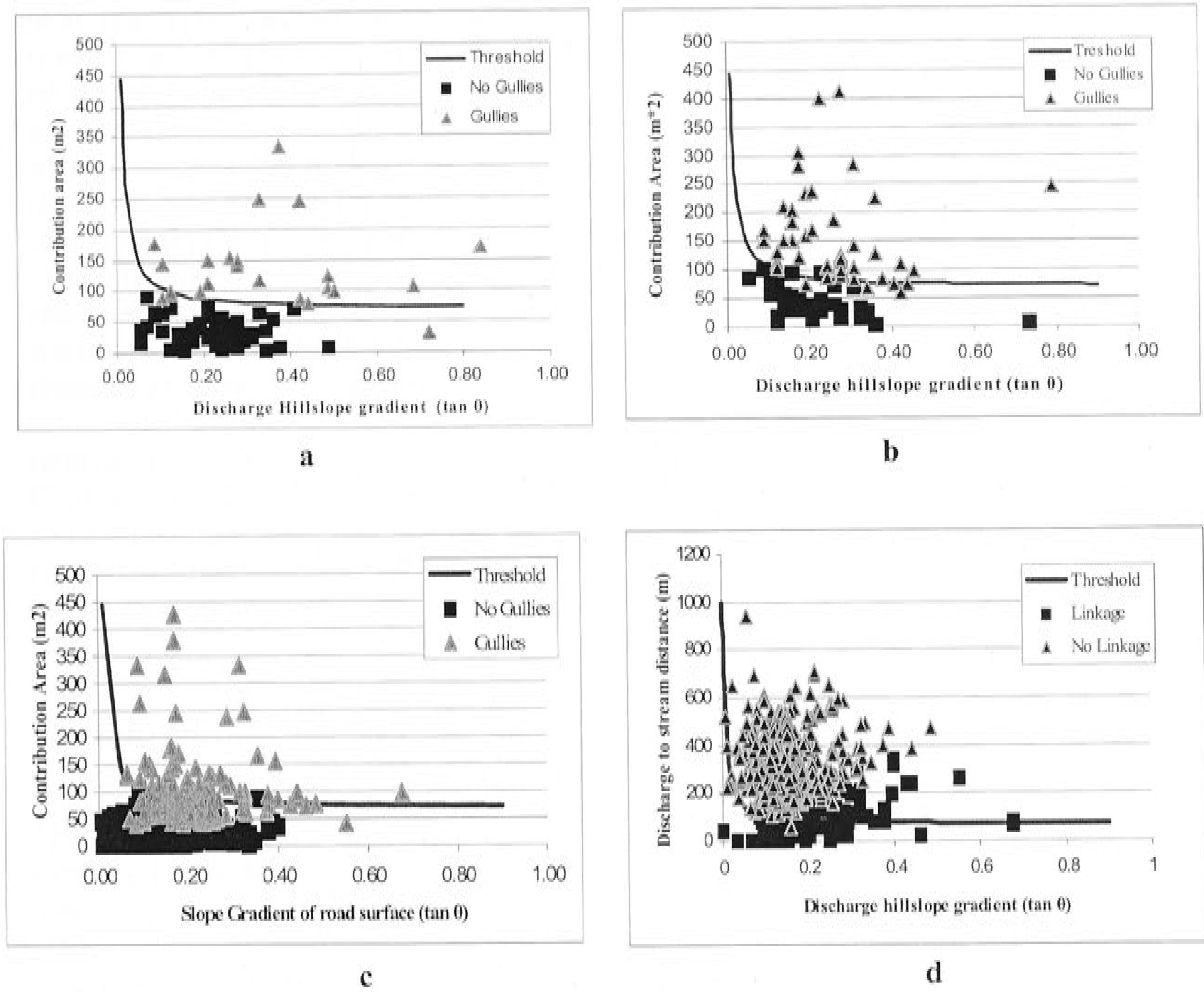

Figure 3. The data with fitted threshold curves (Threshold = m/sinθ where m is contributing road length -m^2 for contributing road area-) separated gully and non-gully at the outlet of mitre drain (a), at the outlet of culvert (b), on the surface of roads (c) and also the road-to-stream linkage (d)

As can be seen from Figure 3 (c), the threshold line based only on the contribution area and road slope did not predict rill and gully initiation or their location on the surface of the roads well. However, there is a strong relationship between the size of contribution area and hillslope gradient with gully initiation. A rill and gully will be initiated where the contribution area and hillslope gradient are greater than 170 m^2 and about 40% respectively. One of the reasons why the threshold curve cannot be a good predictor for road surface erosion may relate to the variable nature of the travelways (road surface). Ruts made by vehicles on the surface of the roads provide an easy route for runoff flow. The greater the volume of the runoff, the greater the expansion of rill and gully over time. According to the preliminary results of the statistical analysis, slope and contribution area were two important variables influencing the rill and gully formation on the surface of roads ((R-Squared = 0.45, P <0.0027).

Preliminary results from the threshold line based on the distance between road drainage outlets and streams and discharge hillslope gradients show that these two factors can almost exactly predict the hydrological linkage between roads and streams (Figure 3d). No connection was found between road drainage systems and streams when the distance was more than 100 m and the slope gradient was less than 15%. There is a lesser possibility of connection between roads and streams where the distance is greater than 300 m unless where the slope gradient is greater than 40%. The field data from this study did not show any hydrological connection between road drainage systems and streams where the distance was greater than 400 m (Figure 3d). Preliminary results of the statistical analysis show that there is a good relationship between distance and discharge hillslope gradient (at the outlet of drains) for the hydrological connection between roads and streams (R-Squared = 0.52, P <0.001). This relationship was stronger when other variables like CTI, SPI and contribution area were added (R-Squared = 0.75, P <0.001). The majority of road-to-stream linkages were associated with high hillslope gradients and lack of enough distance between the road drainage and streams to absorb the runoff from the road. The results of this study show that the threshold, which has been introduced by Croke and Mockler (2001) can be used for finding the relationship between hillslope gradient and contribution length and area. Connectivity between road drainage systems and streams and also rill and gully initiation and channel formation can be identified using this threshold and statistical analysis. This method will be developed in future work in order to further reduction of the amount of fieldwork measurement.

Conclusion

This study examined nearly 690 drainage outlets and 120 rills and gullies on the surface of roads in the SFMA. Analysis has determined the statistically significant features, which indicate the likelihood of a hydrological connection between roads and streams to include: distance between stream and road, hillslope gradient from road to stream, road contribution area, and the value of the "Compound Terrain Index" for the outlets of the drainage systems. Quantification of these factors for each drain and comparison with threshold values, as illustrated in figure 3, would allow managers to determine the likelihood that discharge from any given road drain would result in discharge (and hence sediment) reaching the stream. This would identify the critical drainage points on each road for which maintenance (or re-design) was of high priority.

Acknowledgments

The authors gratefully acknowledge the logistic and financial support of University of Gorgan (Iran), the ANU Forestry Program (SRES) and Forestry and Forest Products of CSIRO and also Sue Holzknecht (SRES) for editorial assistance.

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MODELING THE HYDROLOGICAL CONNECTION OF FOREST ROADS AS A SOURCE OF SEDIMENT TO STREAMS

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ABSTRACT

The essential viability of fluvial systems and their water quality is extremely sensitive to pollution including loading by sediments. Any agricultural or industrial land in a catchment, which drains into streams and rivers, may affect the quality and quantity of the water in the fluvial system. Improvement and adjustments to the land use management system may therefore help alleviate any negative effects on the water and river systems. In forests, unsealed roads have long been recognised as the main source of sediment delivery which results from management (Croke *et al.*, 1999, Anderson *et al.*, 1976 and Patric, 1976). Forest roads closest to watercourses are more likely to pollute water than the ones located far away from the streams because of their shorter flow path and delivery length. Calculating the actual flow length and understanding and modelling the characteristics of the delivery pathway from the outlet of the drainage systems of forest roads to streams is one of the most important aids to managing roads against negative impacts.

The aim of the study presented in this paper was to predict which locations on a road would be most likely to contribute sediment to streams. The method was to calculate and model the flow path and length of runoff delivery, including the possible distance of flowing runoff, from the source of runoff and sediment to the stream network using GIS models. The system was developed using actual data from Stromlo Forest ACT, Australia as a case study site. The results have shown that the flowlines model did not always accurately predict the distance to stream from some points. The reason was related to the behaviour of the flow lines model, which predicted the flow to take a lengthy.

zigzag path along the streamlines rather than joining the stream. The flowpath model, which uses a flow direction grid to define the distance from the drains to the streams,gave more accurate results compared with other models; and the distance to streams that was measured in the field.

INTRODUCTION

Land use management systems, especially forest engineering activities such as timber harvesting and forest roads formation have long been recognised as the main sources of sediment affecting the quality and quantity of water in fluvial systems. Forest road managers always are concerned about the condition of the roads during forestry activities such as timber transportation. Because of that, road maintenance has been mostly focused on draining the road surface and keeping the roads serviceable. However, over the past two decades, concern by the public and scientists about the effects of forest roads on soil and in - stream water quality, have made managers more concerned about the off-site effects of forest roads. Sheet erosion is a common problem for almost all unpaved forest roads. This problem will not harm the in - stream water quality unless the flow reaches the stream. Therefore, the off-site effects of the roads are mostly related to the connectivity of the road and stream based on the possibility of the runoff flow reaching to the stream from the outlet of the road drainage systems. New technology such as GIS software and the capability of computers help the scientist and managers to determine this probability by modelling the flow.

GIS software has become one of the most important tools for developing geographical, geological and hydro hydrological models and watershed management systems. *The National Research Council of USA* (1999) reported that GIS is a powerful new tool for the collection, storage, management and display of map-related information that can provide decision-makers with interactive tools to better understand and judge how the actions of management might affect a natural system. In watershed management systems, it is very important for researchers and managers to identify the possible sources of impacts (e.g. soil erosion) to streams. Wilson *et al.* (1999), argued that GIS has allowed users to predict essential values and data at any point within the watershed and to run both traditional and new models more efficiently by partitioning entire watersheds into smaller sub-watersheds. They also reported that most of lumped parameter models such as MODFLOW, HEC2, and SWAT have been linked to GIS to predict surface and ground water flows. These applications and assessments take many different forms and are applicable to many different areas such as forest roads as well as water quality issues.

Digital Elevation Models (DEMs) are useful GIS layers that can be used for automatic delineation of flow and stream networks and watershed analysis. They can be used to create terrain attribute maps, data and finally to determine channel and drainage density using GIS software. Calculation of flow direction and upslope areas using DEMs are a major part of hydrologic modeling. The procedure is based on representing the flow direction, derived from DEM, as an input by determining the steepest downwards path after partitioning of flow among eight potential pathways to a neighboring (D8) grid cell. Gallant and Wilson (2000), Tarboton (1997), and Moore *et al.* (1991) argued that calculating the flow direction from DEM is necessary in hydrologic modeling to determine the flow path of the water, sediment and/or contaminant. Flow direction is also used for calculating upslope contribution and specific catchment's area, which are the two most important distributed terrain attributes, which determine flow and sediment transportation.

Since the 1990s when the use of terrain attribute analysis in GIS was developed by Moore and Wilson, watershed assessment and management has improved dramatically. These authors and others have pioneered and developed viable GIS applications, computer programming and mathematical support. The calculations they have developed, have contributed to watershed and surface water modelling and management (Lyon (2003) cited from Maidment and Djokic, 2000). GIS has been used to vary model inputs and compare model outputs, such as forest engineering systems, with field data in the hope of improving the scientific basis of key water quality management plans.

Modelling, calculating, predicting and/or estimating the level of road -to -stream linkage (distance) can provide a suitable tool to manage the streams and roads against on-site and off-site impacts of runoff generated from the road prism. Runoff and flow behaviour originated from the road prism towards streams should be well represented in order to define the level of connection between the road and the stream. Although erosion and sediment production are common outcomes from road construction and maintenance, these will not cause any problem to streams if there is no road to stream connection. To establish if this is so, it is important to know where the runoff will flow (the direction), where it may concentrate (based on the flow direction and contribution area draining a specific drainage system) and finally where it is most likely to link to watercourses.

Finding the key to reducing soil erosion which may lead to sediment delivery to an adjacent stream resulting in water quality degradation is essential if forest road systems are to be managed effectively. One of the main aims of this paper is to answer the question, 'how can the spatial analysis and visualization capability of GIS can be used to improve parameter estimation or determination related to forest road management systems?' This paper also discusses the possibility of automating the calculation of the road-to-stream linkage (distance) using GIS network analysis, flowlines and flowpath GIS analysis functionality applications.

METHODS

The map of the entire region included the case study area (Stromlo Forest, ACT, Australia) has been digitized and the watershed and catchments areas have then been separated from the original map for further study (Figure 1). Stromlo Forest and the adjacent area are a small part of the Murrumbidgee catchment area draining to the Molonglo River. A Digital Elevation Model (DEM) was created using ANUDEM and ArcInfo. DEM was then analysed and terrain attribute maps such as slope, aspect, curvature, Compound Topographic Index (CTI), Stream Power Index (SPI) and upslope contribution area were derived from the DEM and have been used as input for model application. The entire Stromlo Forest Management Area (SFMA) as a small watershed has been delineated using DEM analyses in order to create stream networks, sub-catchments or sub-watersheds and their exact position on the ground estimated. The watershed was delineated using basin and hydrologic modelling extension in the ArcView, ArcInfo commands and also TauDEM WinMap.

The hydrologic modelling and watershed delineation processes are shown in Figure 2. The DEM of the study area was used as an input layer. The first step is to fill in the sinks (areas which will not drain anywhere) in the elevation grid. Cells that do not drain anywhere may, become a problem to the process of building a drainage network system that defines the flow path. The next step is to create a flow direction network from the filled DEM. Flow accumulation is used to identify the downstream cells. These were used to create the stream network, stream order, stream length and points of reach. The watershed outlet or "pour point" was created using flow grid and reach point inputs, finally this layer was used for creating the watersheds (Figure 2). Watershed areas, mean of elevation, mean of slope, stream flow length and high and low positions of the stream were also calculated by the watershed delineation process.

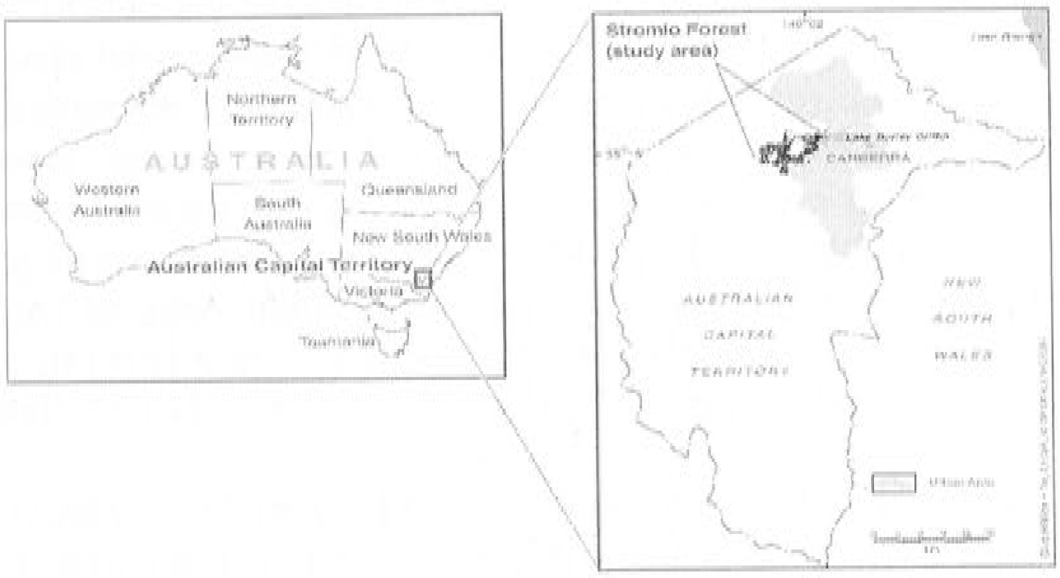

Figure 1: Location of the study area

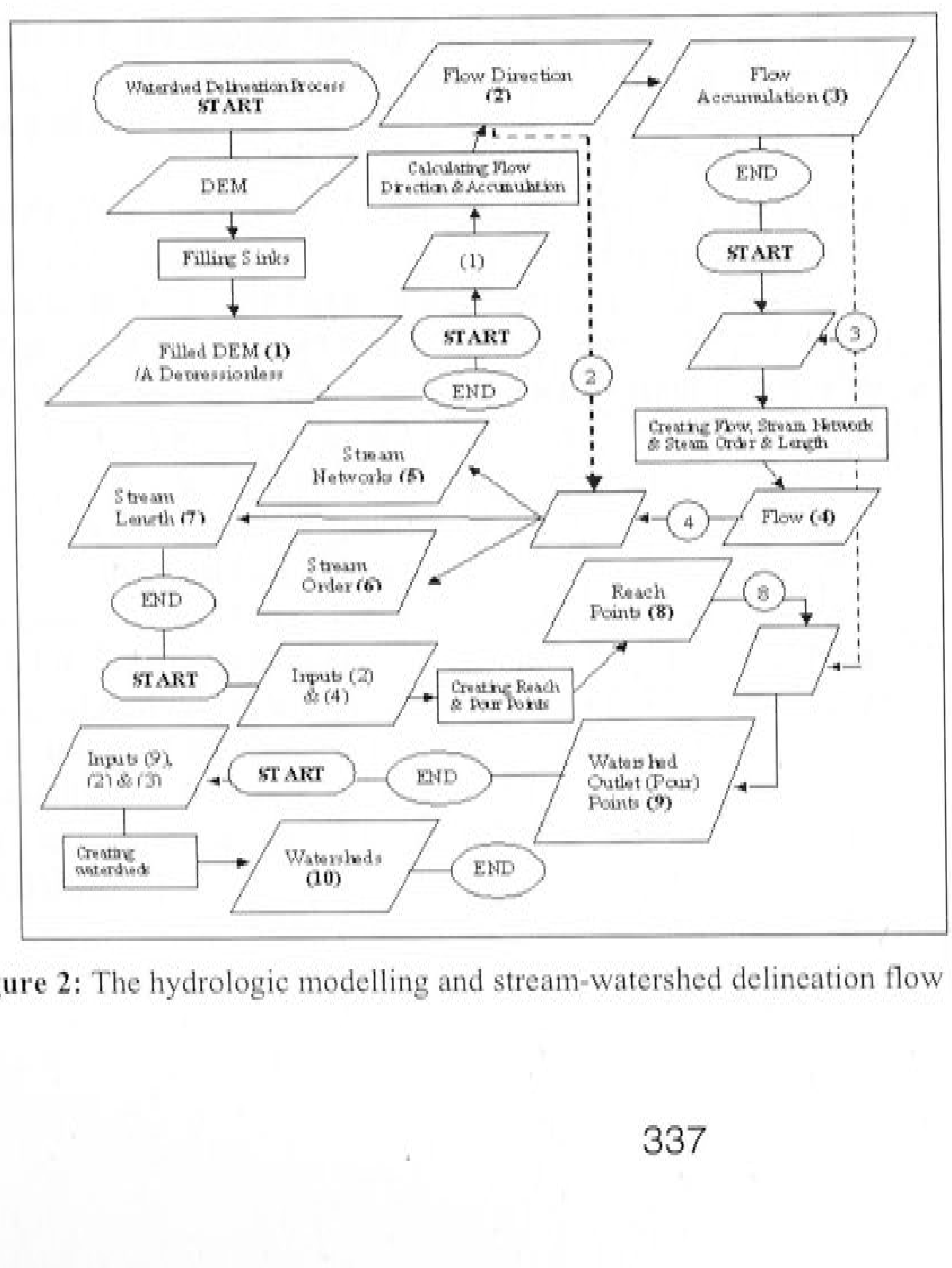

Figure 2: The hydrologic modelling and stream-watershed delineation flow chart

The location of the forest road prisms and drainage systems such as miter drains and culverts has been gathered from the field using GPS and then transferred into ArcGIS and stored as a GIS databases and layers. Data was been stored in multiple files and all data contains a unique coordinate system that identifies the position of each data point in the field (Stromlo Forest). A database of individual files, which contains drains, road layout, and characteristics of the terrain, was developed and complemented by adding some data extracted from the terrain attributes of the related terrain layers.

The distance between road drainage systems and streams was calculated using ArcInfo commands and algorithms to determine the connectivity of road and stream. The ArcInfo commands have been written in Arc Macro Language (AML) using some algorithms such as Patricletrack (the particle tracking algorithm) and coding the function of water movement behaviour on the ground (Takken, 2003). The processes of calculating the distance are shown in Figure 3. The stream coverage and stream grid were created from the existing stream network (from the watershed delineation process) using ArcInfo and were then used as other input layers. The field data related to the road drainage systems, that have been previously stored as multiple files, were used as drain point vector input layers, separately for culverts, miter drains and rills and gullies.

The ArcInfo *NEAR* method has been used for determining the distance between the outlet of road drainage systems (point) and streams (line). The arc *NEAR* model determines a point-to-arc, point-to-node and point-to-point distance. The locations of the road drainage systems (point coverage) and stream network (line coverage) have been used as input layers. The distance was computed from each outlet drainage point to the nearest streamline. The output includes the all of the attributes from the input point coverage, which will be copied during the process, and the calculated distance that will be added during the application. The *NEAR* application process, therefore, will not affect the input files and their coordinate precision.

The *FLOWLINES* program has been written, based on the particle-tracking algorithm that is known as 'particletrack', and the grid function and code (Takken, 2003). This model predicts the direction and future location of a flow, based on the local velocity field by interpolating the nearest grid (e.g. elevation grid) cell centers. The output of this model is a line coverage file within flowlines. The flowlines start at the outlet of drain and flow all the way down until they reach the edge of the grid (DEM) and join a streamline. These flowlines intersect with streamlines using sflines code (Takken, 2003). The output of these processes is a distance file that includes the length of flowlines from the outlets of the drains to the stream using the stream coverage within a buffer zone. A FLOWPATH model has been written, based on the grid function and flow direction (Takken, 2003). The model uses the flow direction grid to define the distance from the outlet of the drain to the stream. The program calculates the flowpath starting from the grid cell at the outlet of the drain and then follows the flow direction down the grid until it reaches a grid cell that has a streamline. The distance between drain and stream is the length of the calculated flow path that has been written by the model in the end of the process (it has been named GRIDPATH).

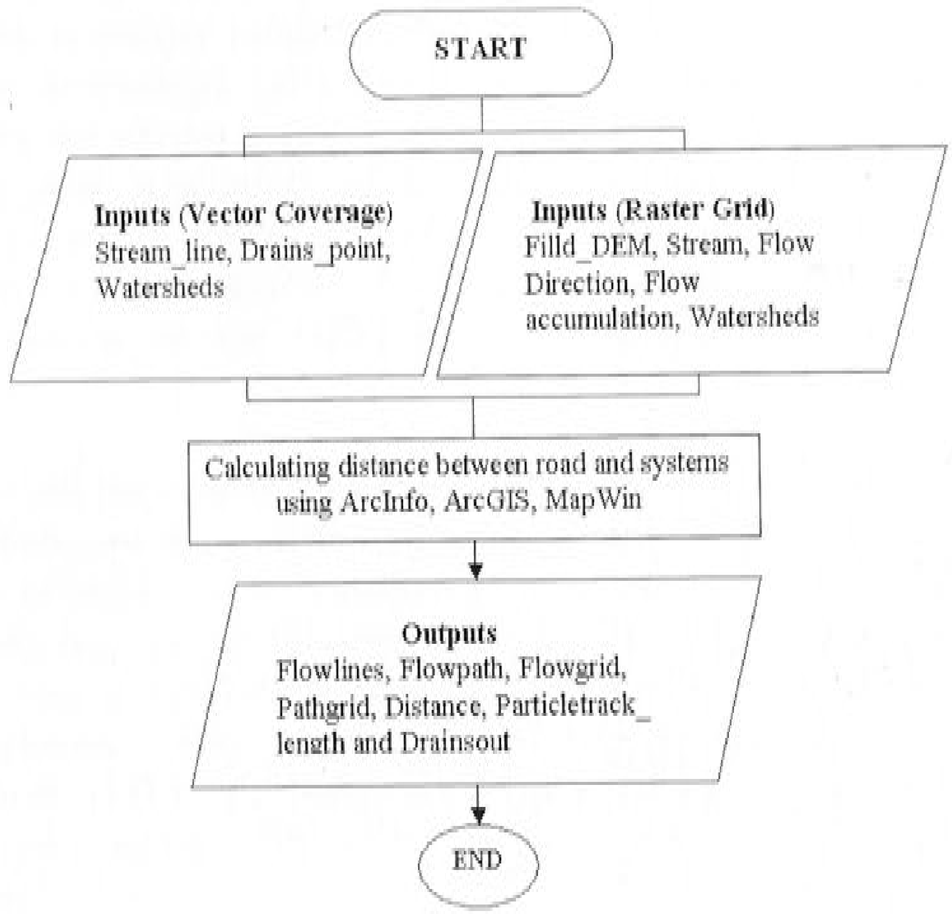

Figure 3: GIS_ Based flow chart model

The distance has also been calculated using the TauDEM extension for ArcGIS and WinMap by a network analysis process. A DEM grid file was used as input file and the distance was calculated using watershed delineation, network and DEM analysis. The distance between each drain to stream has been extracted from the grid output using ArcInfo commands and AML (it has been named DISTMW4). The process of calculating the connectivity between drain and stream in the DISTWASH model is almost the same as most of the models, which are mentioned above. DEM, flow direction, stream networks and watershed grid have been used as input layers and the output layers was a grid file from which the distance data can be extracted using ArcInfo commands based on the location of the drains.

In order to compare and assess the results of the different estimation procedures, GPS was used on a random sample (about 1/3) to measure actual the field road drainage to stream path lenghts. The visible evidence of the flow path from the outlet toward the stream enables the author measure the actual flow distance on the ground. Measurement of flow pathswas based on the topography slope direction, depression and any other evidence that showed where water would have flowed from the outlet down to the stream. The results of the models were compared with the distance obtained in the field using regression and sensitivity analysis.

RESULTS AND DISCUSSION

The results of this study show that an accurate DEM with good positioning of the stream is necessary when correctly determining the distance between the outlet of the drain and streams. Accurate flow direction is also important as it used both as raster (grid) and vector files for creating other output files. The accuracy and correct determination of the direction of the flow is mostly related to the accuracy of the input file (DEM). The reliability with which the downslope cells or flow accumulation is determined, is very important for positioning the stream network, and is mostly related to the accuracy of the direction of the flow. The level of accuracy of the road-to-stream connectivity is related to the level of the accuracy of stream network positioning. Some outputs of the watershed delineation process are shown in Figure 4. As can be seen from this Figure, the stream is laid down in the correct position on the DEM and the sub-watersheds are calculated from the stream network.

As mentioned previously, this study compared several alternative methods of estimating the distance between the outlets of the drain and the stream from a DEM. The results of the different methods were compared with the measured distance from the field. The comparison has shown that two models (Flowpath and Flowlines) predicted the distance more accurately than others, based on correlation analysis (Figure 5 and 6). Figure 6 shows the correlation matrix between distance to stream as determined from the field measurement (FIELDDIS) and six other potential indicators. The best prediction is clearly gridpath (correlation coefficient $r = 0.93$, $r^2 = 0.86$ and $p = 0.000$) (see Figure 5 and 6 and Table 1 and 2).

The flowlines algorithm was not worked accurately for some of the drain points; the flowlines could not reach the stream properly for nearly 5% of the point coverage. Some flowlines were correctly located from the outlet of the drains and the path to the stream was correctly simulated, but they did not join the stream grid cell correctly. The flowlines followed a lengthy zigzag path along the streamline (Figure 7). However, for most drains the flowlines are calculated drains correctly. The points (about 30) in which the flowlines predicted the wrong movement and direction have been taken out (before correlation test) from the analysis and comparison process because of uncertainty of the results. The PTRALEN distance (the result of flowlines and sflines) has the second best level of correlations (r: 0.87, $r^2 = 0.75$ and $p = 0.000$) (compared with distance determined from field measurements) after taking out the drains that had anomalous prediction (Tables 1 and 2).

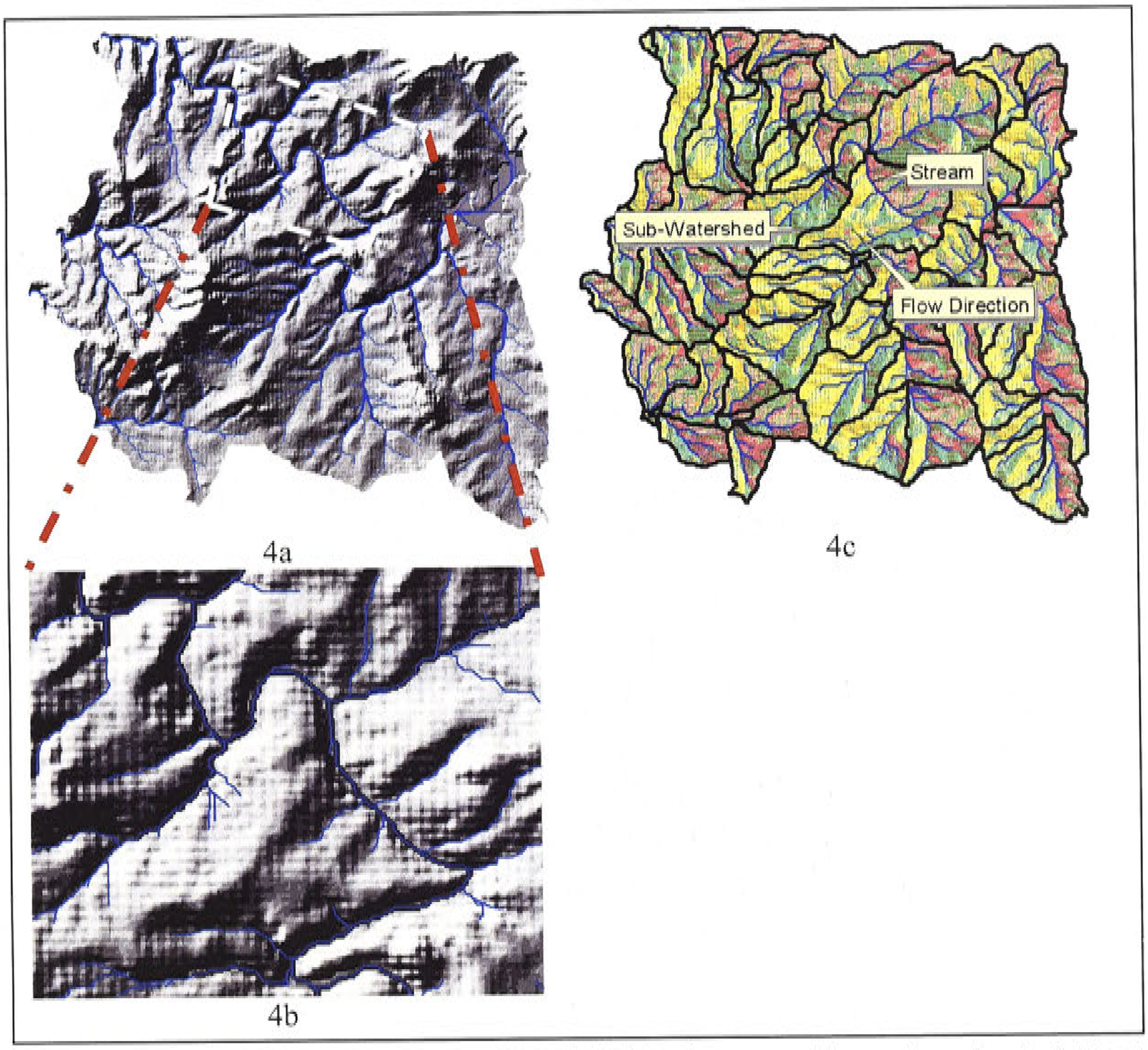

Figure 4: Watershed delineation results, hillshade DEM and stream position on the surface (a & b) and sub-watershed (c)

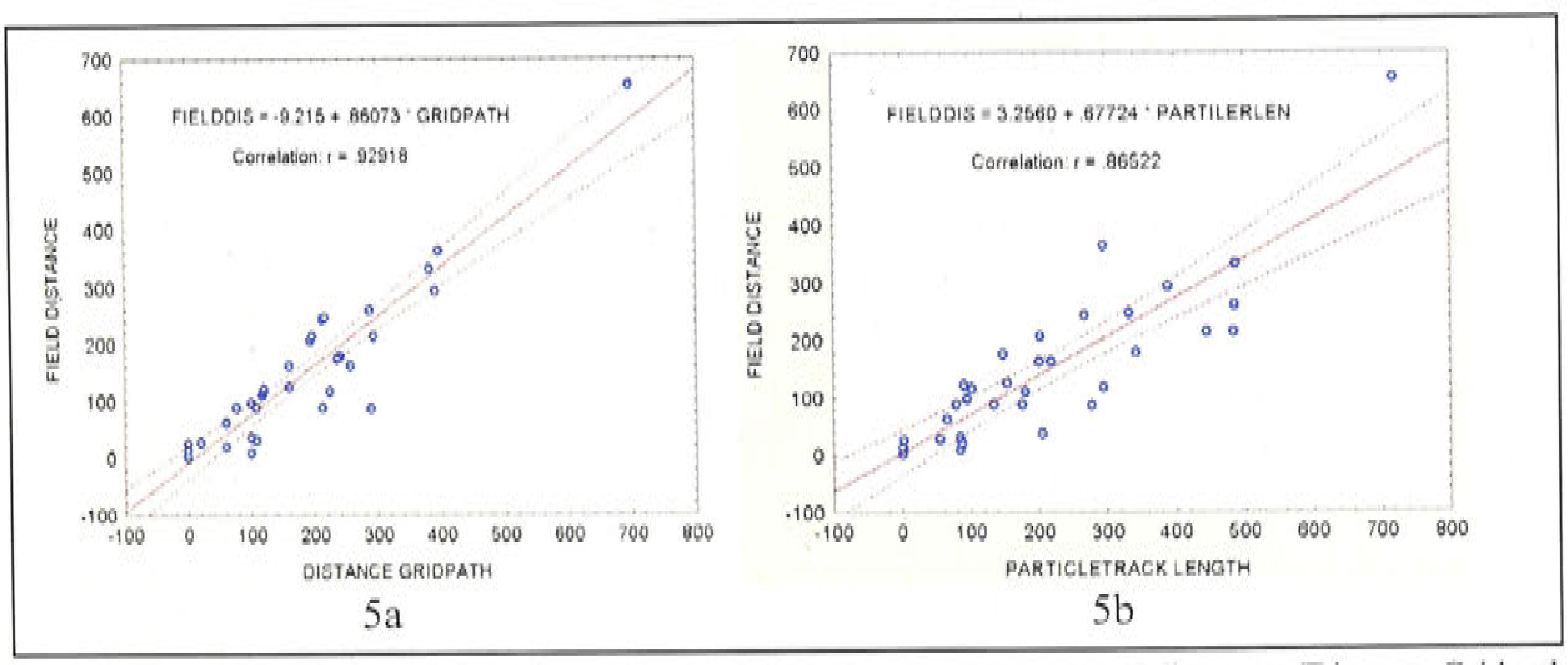

Figure 5a & b: Regression and correlation comparison between predicted distances (Distance Gridpath (a) and Particletrack length(b)) and field-determined distance (Field Distance)

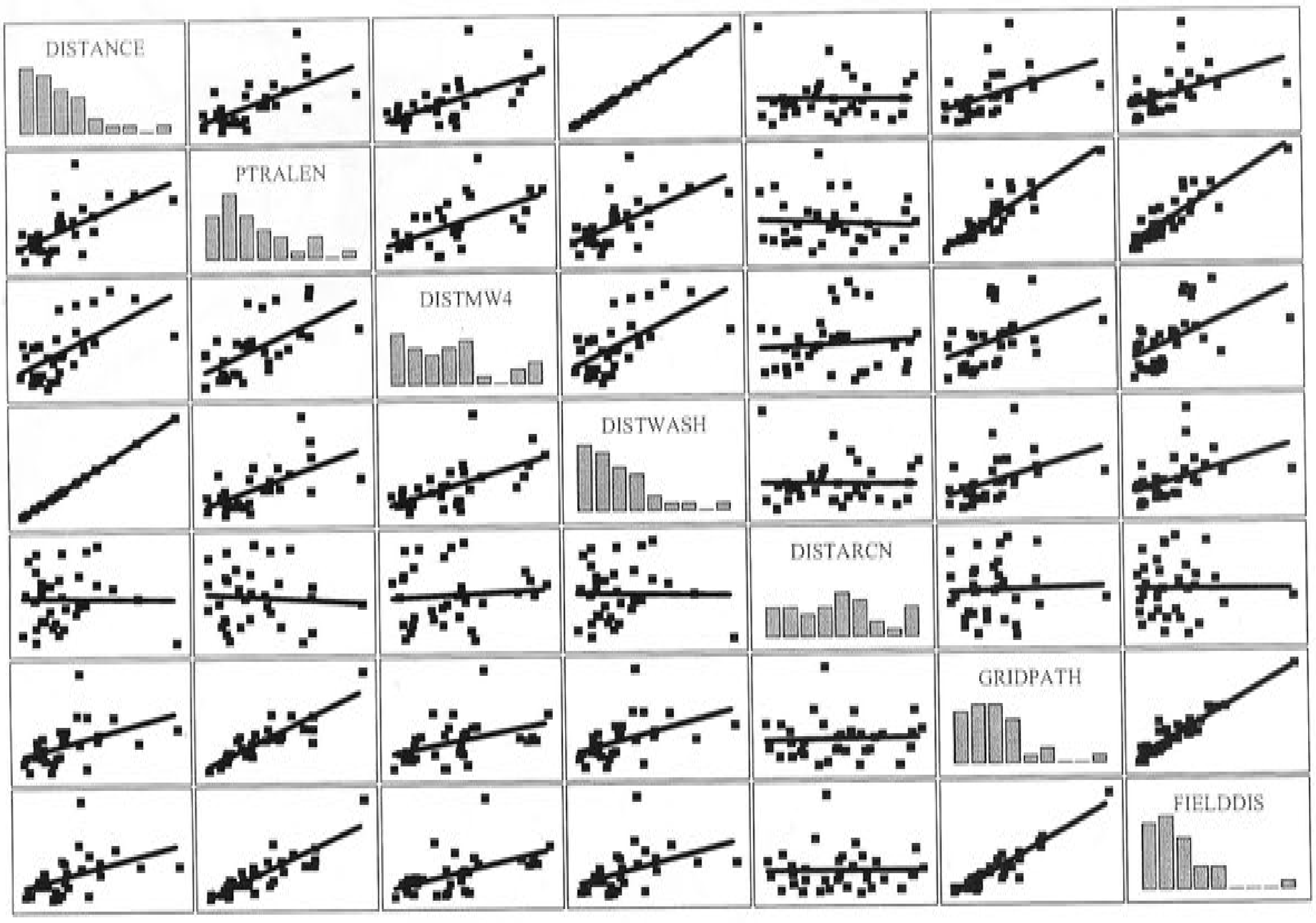

Figure 6: Correlation matrix between the field distance and predicted distances

Table 1: Correlation results between field distance and predicted distance using different models

Models	Field Distance	GridPath	PtraLen	Distance	NEAR	DistMwin	DistWash
FIELD DIST	1.00						
GRIDPATH	0.93	1.00					
PTRALEN	0.87	0.88	1.00				
DISTANCE	0.45	0.46	0.62	1.00			
NEAR	-0.005	0.04	-0.08	-0.02	1.00		
DISTMWIN	0.53	0.43	0.61	0.62	0.08	1.00	
DISTWASH	0.45	0.46	0.62	1.00	-0.02	0.62	1.00

Table 2: Summary of Statistical results (Parameters Estimation and Effect Test)

FIELD DISTANCE								
Models	**R**	**R^2**	**Effect test**		**Parameter Estimates**			
			F Ratio	Pro.F	t Ratio	Pro.t	Mean	St.dev
GridPath	0.93	0.86	195.9	0.00	14.0	0.00	186	143
PtraLen	0.87	0.75	92.31	0.00	9.61	0.00	218	169
Distance	0.45	0.21	8.07	0.008	2.84	0.008	317	251
Near	-0.01	0.00	0.001	0.98	-0.03	0.98	173	72
DistMwin	0.53	0.28	11.97	0.002	3.46	0.002	526	397
DistWash	0.45	0.21	8.07	0.008	2.84	0.008	317	251

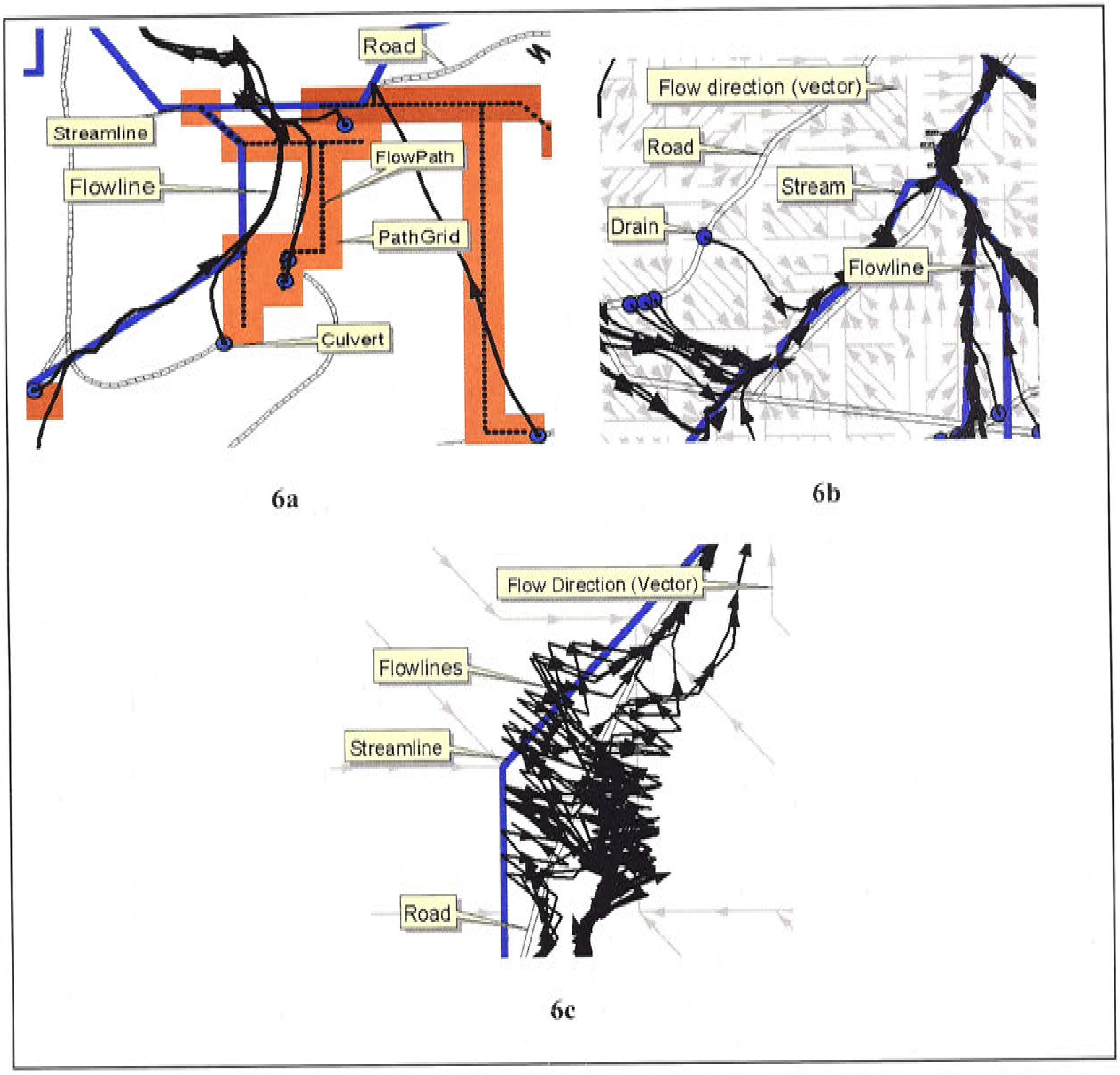

Figure 7: Indicates the Flowlines calculated from the outlet of drains to stream and their wrong prediction along with a lengthy zigzag flow along the streamline (7b & 7c), and movement comparison among Flowpath, Gridpath and flowlines (7a)

CONCLUSIONS AND FURTHER WORK

The increasing availability of computer programming and GIS datasets has encouraged the development of GIS_ based modelling techniques. This study shows that using a GIS in combination with mathematical (algorithm) and hydrological models is very useful for determining the level of road-to-stream connectivity by calculating the distance between the outlet of drain and stream. Hydrologic modelling and/or stream delineation play an important role in forest road management, especially in managing the road to stream hydrologic connection. Furthermore, the paper describes the development of an automated road-to-stream distance calculation using GIS_ Based model application (computational algorithms). The results of this (automated distance calculation) are very useful for managing the roads in order to prevent stream water deterioration and hydrologic connectivity, and will also reduce the amount of field work and therefore reduce the cost of evaluations. The results of this study have also identified a method of calculating the distance between road and stream much more accuracy than other applications when compared with the field measured distance. Further work will involve: using the prediction of road-to-stream distance to determine connectivity, improving the delineation of the watershed and finally testing the model system by comparing predicted with actual results determined from the field.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the logistic and financial support of University of Gorgan (Iran), the ANU Forestry Program (SRES) and Forestry and Forest Products of CSIRO. The author also gratefully acknowledges Dr. Ingrid Takken from Australian Defence Force Academy (ADFA), the University of New South Wales for her great help and for writing the AML. I also thank Dr. Ryde James, Bob McCormack, Jacky Croke and Sue Holzknecht (SRES) for their scientific and editorial assistance.

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6. **Poster presented at the Twenty Second IUFRO World Congress, Brisbane, 8-13 August 2005.**

A new approach to the environmental risk assessment of forest road systems—mitigating the risk of stream deterioration

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Unsealed forest roads are the main source of sedimentation in streams. This risk is highest during road construction and when maintenance is poor. Identifying problems locations, analyzing, and ranking the risks can be useful when managing the road to mitigate harmful impacts to stream water quality.

The aim of this study was to develop a method for assessing the risk for existing unsealed forest roads. Field data and information were gathered from a case study area (Stromlo Forest, ACT, Australia) using DGPS, and then transferred and stored as a GIS database in layers. Terrain attributes data and maps were derived from a digital elevation model. The most important variables to the risk of forest roads affecting the initiation and expansion of rills and gullies on the surface of the roads and at the outlets of drainage systems were then determined using logistic regression analysis. The effective variables were then overlaid using ArcView, ArcGIS, and IDRISI to create a "risk map of the study area". The results show that slope, contribution area, CTI, and distance between roads and streams are the most important factors affecting the elements at the risk (soil and water).

These results will help decision-makers to more effectively manage their roads by identifying specific road locations where problems are likely to occur. This method can also be used as a framework for evaluating environmental risks of unsealed forest roads.

Keywords: Forest Road, Risk Assessment, stream deterioration, GIS, Impacts

7. Abstract of paper presented at the International Congress on Modelling and Simulation (MODSIM2005), Melbourne, 12-15 December 2005.

Using GIS, Terrain Attributes and Hydrologic Models to Predict the Risk of Soil Erosion and Stream Water Deterioration Cause Forest Roads

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Unsealed forest road network may generate negative impacts on adjacent soil and water values by changing the quantity and quality of water and delivery of sediment to the stream. Predicting the risk for road network on the quality of stream water has increasingly become a major task in relevant scientific research, in order to respond to the concerns of the public, environmentalists and forest managers. This study is an attempt to develop an integrated methodology for Forest Road Impact Assessment (FRIA) in relation to soil erosion and stream water deterioration using GIS techniques, terrain attributes and hydrologic models.

The overall approach in forest road planning and maintaining processes at the local, watershed or regional scale is to be able to simulate, predict, and remedy or mitigate the impacts of the forest road on the elements at risk; in an efficient way. The feasibility of predicting the likelihood of sheet erosion occurrence along the road systems and risk of this to the stream water quality were explored using some terrain attributes as indicators.

All relevant terrain attributes were created from a DEM initially at 20 meters resolution using Digital Terrain Analysis and DEM filtering to parameterize the attributes. Field measurements were carried out to gather data using a DGPS from randomly selected roads (study area in Stromlo Forest) to validate the hydrologic setting and assess the accuracy of relevant data and mapping. The collected and derived data were tested using standard and canonical correlations and also multiple, discrimnant and logistic regressions.

The result of this study shows that the integration of the GIS analysis, terrain and hydrologic modelling is an efficient way to predict and simulate the effect of forest roads on the elements at risk. The results show that some terrain attributes such as slope, CTI, contributing road length and area, and curvatures were significant independent variables in predicting the occurrence of rills or gullies on either the road surface or at the outlet of the road drains. Most of these variables are also recognised as the most important factors influencing the road to stream connectivity. The simulated or mapped risk and related information from these processes can be used for planning new roads and maintaining existing road network in order to protect clean stream water against deterioration.

Keywords: Forest Roads, Water Quality Impacts, Risk, GIS, Hydrologic Connectivity